Volume 22 · Issue 1
February 2025

Asian Journal of WATER, ENVIRONMENT AND POLLUTION

ISSN: 0972-9860 (Print)
ISSN: 1875-8568 (Online)

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Asian Journal of Water, Environment and Pollution

Print ISSN: 0972-9860
Online ISSN: 1875-8568

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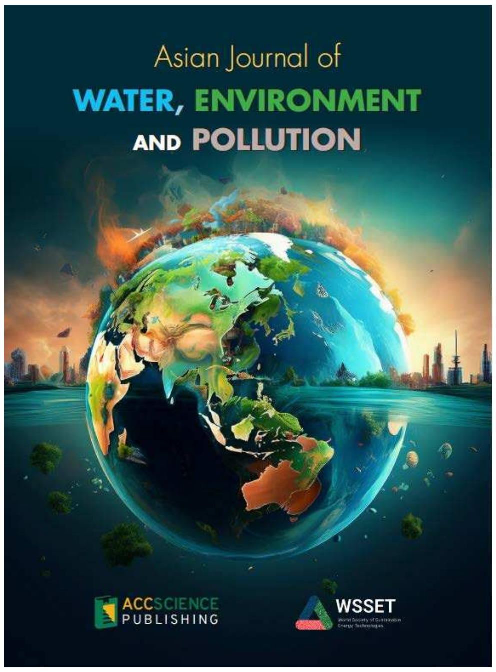

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Volume 22 • Issue 1 • February 2025
ISSN 0972-9860 (print) ISSN 1875-8568 (online)

Asian Journal of Water, Environment and Pollution

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ASIAN JOURNAL OF WATER, ENVIRONMENT AND POLLUTION

ISSN: 0972-9860 (print)
ISSN: 1875-8568 (online)

Editorial and Production Credits

Publisher: AccScience Publishing
Managing Editor: Irene Zhao
Production Editor: Samyuktha Balakrishnan
Article Layout and Typeset: Sinjore Technologies (India)

For all advertising queries, contact ajwep.office@accscience.sg.

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doi: 10.36922/ajwep.8483

ORIGINAL RESEARCH ARTICLE

Promoting sustainable development goals through the Chinese concept of eco-civilization: A Delphi study of priority areas in the China–Pakistan Economic Corridor

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Received: January 10, 2025; Revised: February 8, 2025; Accepted: February 11, 2025; Published Online: February 28, 2025

Abstract: The concept of eco-civilization, or "shengtai wenming jianshe" in Chinese, emerged in academic circles in the 1980s and was officially adopted by the Chinese Communist Party in 2007. This concept highlights the profound harm human activities inflicted on nature, climate, and biodiversity. Given the global environmental challenges posed by human actions and economic activities, it is crucial to promote ecological civilization universally. This paper aims to uncover the key aspects of eco-civilization to address challenges related to the China–Pakistan Economic Corridor (CPEC), a major project under the Belt and Road Initiative. It emphasizes aligning CPEC with green development goals to support sustainable economic progress in Pakistan and China. The study employs semi-structured interviews, a modified four-round Delphi method, and calculates a priority index. The research population includes climate experts, scholars, researchers, academics, policymakers, industrialists, and environmentalists from both countries, providing valuable insights into eco-civilization. Using an iterative approach with continuous feedback informing each round of the Delphi technique allows for systematic conceptualization, evaluation, and ranking of factors to develop a comprehensive priority index. The findings emphasize the necessity of embedding ecological principles in regional development strategies to maximize CPEC's contribution to the United Nations' sustainable development goals. By promoting ecological harmony, resilience, and sustainability, this research offers a strategic framework for leveraging CPEC as a model for sustainable development that could positively impact neighboring regions and global communities.

Keywords: Eco-civilization; China–Pakistan Economic Corridor; Green development; Sustainable development goals; Ecology; Climate change

1. Introduction

In an era marked by escalating environmental challenges and the urgent need to meet the United Nations' sustainable development goals (SDGs), the concept of eco-civilization, originating from traditional Chinese philosophical thought, particularly Confucianism, presents a transformative framework for harmonizing human progress with nature.[1] The term eco-civilization, or "shengtai wenming jianshe" (生态文明建设) in Chinese, gained prominence in academic discussions during the 1980s and officially became a part of the Chinese Communist Party's political discourse in 2007.[1] Eco-civilization emphasizes the delicate interplay between biotic and abiotic systems, advocating for a sustainable approach that respects natural processes rather than dominating them. As "eco" pertains to ecology or the environment, the term "ecology" refers to the intricate relationships between living organisms and their surrounding environment.[2] Unlike conventional development models, which often disrupt the ecological balance, eco-civilization calls for a holistic integration of spiritual, organizational, and material advancements, to create synergy between environmental protection, societal well-being, and economic growth.[3]

Ecological ethics has long been central to Chinese culture, offering a visionary framework that transcends the materialistic focus of civilizations shaped since the Renaissance.[4] Chinese environmentalists have critically examined how the nation's perspectives on global civilization reflect growing environmental challenges. Furthermore, this concept has ignited ongoing debates among Chinese scholars, highlighting its potential to address urgent environmental and climatic crises.[5] The China–Pakistan Economic Corridor (CPEC), a $46 billion project, with $34 billion allocated for energy, has faced criticism for its environmental impact, particularly due to carbon emissions from coal-based projects.[5] However, by adopting China's eco-civilization philosophy, Pakistan could reposition CPEC as a model for sustainable development, addressing environmental concerns while aligning with the broader goals of the Belt and Road Initiative (BRI).[6]

This paper aims to uncover the significant areas in the Chinese vision of eco-civilization that could address CPEC's environmental challenges moving forward. As a mega project within the BRI, CPEC holds the potential to align with global sustainability targets, such as the United Nations' SDGs, particularly those related to climate action and sustainable infrastructure.[7]

2. Literature review

2.1. Theoretical support and analytical framework

Theoretical perspectives, as proposed by Lechner *et al.*,[8] offer frameworks for logically connecting various concepts and processes. A contemporary interpretation of ecological civilization is derived from Wen Tiejun's ideas, which are inspired by the "Rural Reconstruction Movement" of the 1920s.[9] This movement, led by prominent Chinese environmentalists and ecologists, emphasized the intricate relationship between humans and nature. Historically, this relationship has been marked by significant environmental degradation, highlighting the need for a balanced coexistence between human society and the natural world. Zinda *et al.*[10] argue that humans are inherently bio-social beings, dependent on society and the surrounding environment, underscoring the critical importance of the environment in human life.[11]

The concept of ecological civilization is deeply rooted in traditional Chinese thoughts, such as the "unity of man and nature," eco-socialism, and dialectical materialism, offering a comprehensive critique of the interaction between human society and the natural environment.[12] The eco-socialist theory provides a profound framework for understanding ecological crises by emphasizing the metabolic rift – an eco-socialist concept that describes the disruption of natural cycles caused by capitalist modes of production.[13] This theory highlights the inherent contradictions within capitalism that lead to environmental degradation, advocating for a socialist transformation to restore harmony between humanity and nature.[12]

Eco-socialism, as a contemporary extension of eco-civilization thought, builds on this foundation by proposing systemic changes that integrate social justice with ecological sustainability.[11] It critiques the commodification of nature under capitalist systems and calls for the collective management of resources to achieve sustainable development.[12] Prominent eco-socialist theorists emphasize that ecological civilization requires a departure from consumer-driven growth models, advocating instead for an economy centered on human needs and environmental health. This vision aligns with the SDGs, particularly SDG 13 (Climate Action) and SDG 15 (Life on Land), by advocating for equitable and ecologically mindful development.[9]

The integration of ecological principles into socialist frameworks also draws on dialectical materialism, which underscores the interconnectedness of all natural and social systems.[14] By viewing the environment not as a separate entity but as an integral part of societal development, dialectical materialism provides a holistic approach to ecological sustainability. This perspective is particularly evident in China's ecological civilization strategy, which combines Confucian philosophy with modern environmental policy to foster a harmonious coexistence between humans and nature.[15]

James O'Connor's capitalism, nature, and socialism further enrich this discourse by identifying the dual crises of capitalism: economic and ecological.[16] His work emphasizes the interdependence of ecological degradation and social inequality, arguing that resolving environmental crises requires addressing systemic injustices within capitalist structures. This theory resonates with contemporary environmental challenges, advocating for integrated approaches that combine ecological restoration with social equity.[14]

A deeper exploration of ecological civilization reveals its philosophical alignment with the concept of social-ecological transformation, which advocates for a radical rethinking of humanity's relationship with nature.[11] This perspective critiques the anthropocentric tendencies of industrial civilization and promotes a biocentric worldview, wherein all forms of life are seen as interconnected and equally valuable.[12] Drawing on the work of eco-philosophers such as Murray Bookchin, this approach underscores the inseparability of social justice and ecological sustainability, framing environmental crises as reflections of hierarchical and exploitative societal structures.[15]

Finally, the notion of ecological civilization has roots in Soviet-era ecological culture, which sought to balance human progress with environmental stewardship. This framework has been reinterpreted in China as part of its "Ecological Civilization" initiative, which aims to align socialist development with global environmental goals.[11] By embedding ecological values into governance, this model reflects a unique Confucian harmony between humans and nature, alongside modern ecological imperatives, offering a robust theoretical foundation for achieving sustainable development.[14]

Together, these theories collectively provide a rich intellectual foundation for understanding and advancing ecological civilization, emphasizing the need for systemic transformation to ensure the long-term sustainability of human societies and the natural world.[16]

2.2. Ecological sustainability initiative in other countries: A comparison with the Chinese model

The Chinese model of "Ecological Civilization" integrates SDGs into its national policy, addressing issues like climate change (SDG 13), sustainable cities (SDG 11), and life on land (SDG 15).[17] However, compared to eco-models in countries like South Korea and Japan, which emphasize ecological sustainability, China's model leans heavily toward social and economic goals, creating potential policy gaps.[16] Other countries such as the European Union and Scandinavia have been advancing their green development strategies, focusing on renewable energy transition, carbon neutrality, and sustainable agriculture. The European Green Deal, for instance, is a comprehensive policy framework designed to achieve carbon neutrality by 2050 and promotes green innovation and sustainability.[18]

Globally, innovative eco-models are making strides in combating extreme climate challenges. For instance, Denmark's "Energy Island" initiative promotes renewable energy via offshore wind farms, directly addressing SDG 7 (Affordable and Clean Energy).[16] Meanwhile, South Korea's "Green New Deal" integrates ecological sustainability with digital innovation, advancing SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13. These models starkly contrast with China's strategies, which focus on incremental improvements in industrial sustainability, such as eco-industrial parks and circular economy models.[14] Despite progress, China's approach often faces regional disparities in implementing SDG-linked targets, particularly in western provinces.

Moreover, eco-models such as the European Union's "Circular Economy Action Plan" and Japan's "Sustainable City Program" emphasize reducing ecological footprints through technology, recycling, and waste reduction.[17] These initiatives have outpaced China's industrial ecology model, which remains nascent despite its potential. However, Japan and South Korea's success is not purely due to market-driven factors but strong government intervention, technological investment, and international cooperation, achieving reduced ecological footprints alongside economic growth.[18] China's policies, although ambitious in addressing pollution and greenhouse gas emissions, have yet to demonstrate similar success in decoupling economic growth from environmental harm.[19]

Another noteworthy comparison can be drawn with innovative ecological strategies in countries such as India and Canada. India's National Action Plan on Climate Change integrates eight key missions, such as the Solar Mission and Green India Mission, designed to enhance renewable energy use, promote afforestation, and increase water-use efficiency.[16] These initiatives are particularly relevant to SDGs 7 and 15, emphasizing grassroots environmental sustainability. Canada has excelled in leveraging its Pan-Canadian Framework on Clean Growth and Climate Change, which combines carbon pricing, renewable energy expansion, and conservation policies to address SDG 13.[11] These strategies have been tailored to align with Canada's vast natural resources and low population density, demonstrating adaptability to regional needs. In contrast, China addresses domestic ecological concerns and promotes global environmental cooperation.[19]

China's ecological sustainability model stands out for its unique approach to integrating "Ecological Civilization" with rapid economic development. Unlike other models that focus primarily on technological innovations or urban sustainability, China's strategy emphasizes a balanced approach, incorporating social equity, poverty alleviation, and ecological restoration at an unprecedented scale.[15] In 2024, China ranks as the second-largest economy in the world, following the United States (US), and is the leading industrial power. However, China is also a major contributor to global industrial pollution, accounting for 30% of global CO_2 emissions, with the US being the second largest emitter after China.[19] Given these factors, China aims to achieve net zero carbon emissions by 2060, aligning its policies with SDGs.[20] However, the US–China trade conflict and the war in Ukraine have hindered the progress toward the SDGs in China. To remain on track, China must fully embrace the concept of eco-civilization.[11]

3. Research methodology

This study employs an exploratory research design grounded in a qualitative methodological approach to explore the applicability and implications of the ecological civilization concept, particularly in the context of China's vision and its potential adaptation to the CPEC. The Delphi method was utilized as the core research framework to achieve the objectives of this study. This method, characterized by iterative rounds of structured and semi-structured surveys, was instrumental in synthesizing expert insights and deriving consensus on critical research questions.[21] In addition, statistical tools, such as Statistical Package for the Social Sciences (SPSS), were employed to develop a priority index, enabling a robust analysis of the collected data.

3.1. Research framework

The research framework is based on the study's research questions. Each phase in the framework is based on experts' responses in the previous phase. Figure 1 illustrates the flow chart of the research framework of the study. This Delphi technique in Figure 1 was structured into four iterative rounds and designed to progressively refine and prioritize the study's research objectives. Each round is built on the findings of the previous one, ensuring a systematic approach to consensus-building.

3.2. Research questions associated with the research framework

The research framework was explicitly designed to address the study's central questions and ensure coherence across all Delphi rounds. Each research question was linked to specific Delphi phases:

(i) Question 1: What is currently driving China's vision? This question traces the origin and development of the concept of ecological civilization in China, highlighting its inception and key influences.
(ii) Question 2: Is the Chinese vision of eco-civilization implacable in CPEC? This section focuses on the implication of possible steps of ecological civilization in the CPEC project.
(iii) Question 3: How is eco-civilization possible in CPEC? This section outlines the roadmap for implementing ecological civilization.
(iv) Question 4: What is the main purpose? Formulating important questions to identify problems and develop an approach using the Delphi method, while addressing these questions within an appropriate scope.

Hence, the research framework of the study addresses and connects all these questions. It also outlines the core concepts behind each question and the Delphi rounds.

3.3. The rationale of each Delphi round

The Delphi technique was structured into four iterative rounds, each designed to progressively refine and prioritize the study's research objectives.

(i) Round 1: Conceptualizing core elements

This round defined foundational concepts, focusing on the theoretical framework of ecological civilization. A structured, close-ended questionnaire identified key variables such as ecological governance and sustainable resource management within the CPEC context, ensuring clarity and alignment.

(ii) Round 2: Investigation or exploration:

Using insights from Round 1, an open-ended questionnaire deepened the analysis of eco-civilization principles in CPEC infrastructure. This phase provided rich qualitative insights.

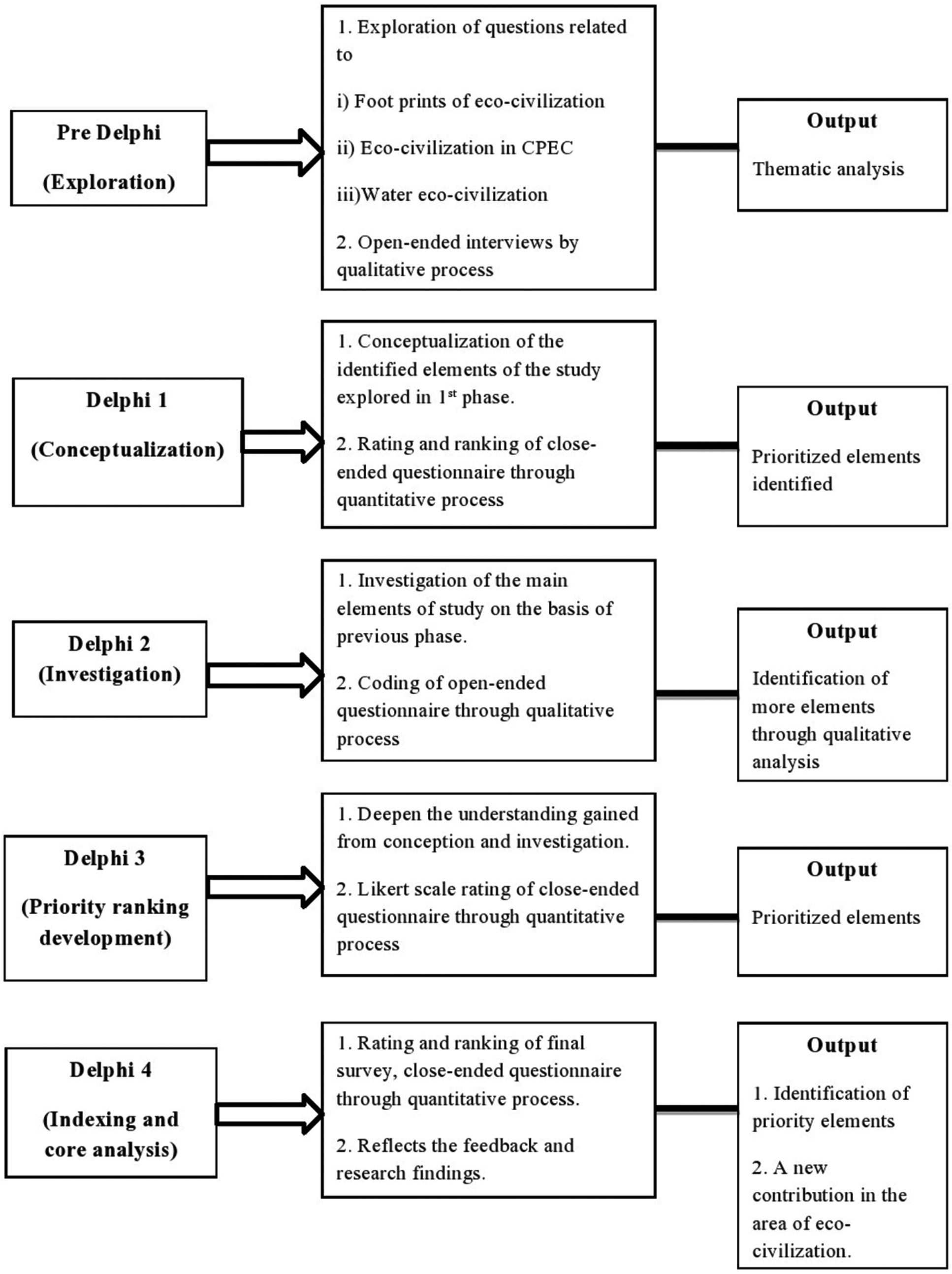

Figure 1. The research framework of this study

(iii) Round 3: Prioritization:

Broad concepts were refined into sub-themes, including water management and industrial ecology. A close-ended questionnaire ranked these sub-elements, using quantitative techniques to validate and align themes with expert consensus. Sub-elements were developed into measurable indicators ranked on a Likert scale.

(iv) Round 4: Indexing:

Analysis of variance (ANOVA) and SPSS software were used to validate these rankings, integrating qualitative and quantitative data to provide actionable insights. The surveys were rated and ranked to reflect the feedback and final results.

3.4. Development of questionnaires

3.4.1. Delphi round 1

The exploration of the elements provided insights into various important views, ideas, and factors of ecological civilization. In Table 1**,** one element from the first key factor is highlighted as the sample of the Delphi round 1 questionnaire.

3.4.2. Delphi round 2

The objective of this open-ended questionnaire is to examine the main themes of the study for further operationalization. Table 2 presents a sample questionnaire of the first theme of the 2nd round questionnaire.

3.4.3. Delphi round 3

Based on responses to the questionnaire in round 2, a new questionnaire was developed for this round, with three items under each theme. Participants were asked to respond to questions related to each item to assess the impact factor of elements of the study. This is a close-ended, rating scale questionnaire. Table 3 presents the questions posed to the participants regarding the footprints of ecological civilization.

3.4.4. Delphi round 4

In the fourth and final round, based on the responses of all previous rounds, a final survey questionnaire was designed and a priority index was created. Feedbacks from experts were used to create the priority index. Table 4 presents a sample of the fourth round questionnaire, which was completed through in-person meetings and interviews with various experts.

3.5. Data analysis techniques

Data analysis was conducted iteratively throughout the Delphi process, employing a mixed-method approach that combined qualitative thematic analysis with quantitative statistical techniques. Open-ended responses were analyzed using content analysis,

Table 1. Sample question of Delphi round 1

Aspect 1: Origin of ecological civilization		
Findings from the pre-Delphi bring out five indicators in the first main aspect of the study. Consider the evolutionary aspects of ecological civilization please rate these five indicators for their impact factors and prioritized elements. Please rate the impact and priority of this aspect on the scale below and give a score out of 100, taking into account the points listed below.		
Statements	**If you agree, please correspond**	**If you disagree, please indicate why you disagree**
1. Environmental and social imbalances		
(i) Earth's ability to sustain itself and its natural system is diminishing the natural resources		
(ii) The growth and happiness of human beings depends upon the connection between humans and eco-systems		
(iii) Growth of human population and mass destruction creates the necessity of collective choice.		
(iv) The social connections of life are greatly disturbed by ecological inequalities and ecological displaces.		
Impact on the evolution of ecological civilization	0 50 100	
Priority given	0 50 100	

Table 2. Sample questionnaire for round 2

Key element 1 – Advancing the concept of the Chinese vision of ecological civilization
Based on round 2 of this Delphi study, one of the most significant elements in advancing the concept of ecological civilization is a reconciliation of humanity and social and environmental imbalances. We want to see the linkups to overcome destruction and unsustainability in the environment. There is a need for useful indications forward for the new ideas and concepts in this Chinese vision. The first highly influential indicator under this key element is Reconciliation of humanity • Environmental unsustainability and irregular climatic patterns • Lack of awareness of ecological and green development concept • Gap in the harmonious relationship between humans and nature
Please tell us how the reconciliation of humanity is possible to urge humans to understand this concept of ecological civilization.

Table 3. Sample questionnaire for round 3

Category 1: Reconciliation of humanity					
How much impact do you think these statements can have in the reconciliation of humanity?					
Statements	**Impact factors**				
	No impact	**Low impact**	**Some impact**	**High impact**	**Much impact**
There is a need to understand emerging ideas and possibilities of the vision of eco-civilization and the purpose of the creation of the universe					
To resolve rapidly deepening human crisis, mindsets need to be changed with the institutions that created it.					

Table 4. Sample of the final round of survey questionnaire

Statements	Grading				
Leveling or extent 2=Low level and 10=Higher level	2	4	6	8	10
Q3. Similar to Marxist capitalism, the present world system has exploited natural resources and created conflicts					
A. Lack of understanding of rational management					
B. Transformation of productive forces into destructive forces					
C. The failure to count the difference between renewable and non-renewable energy					
D. Any other					

Note: Grading: 2: No impact; 4: Low impact; 6: Some impact; 8: High impact; 10: Much impact.

identifying recurring themes and patterns. Close-ended data were analyzed using descriptive and inferential statistics, with ANOVA to compare group means and validate the significance of ranked indicators. The integration of SPSS software (30.0.0) ensures precision and transparency in data handling.[21] Statistical significance was set at $p \leq 0.05$.

3.6. Selection criteria for Delphi participants

The selection of participants, shown in Table 5, was driven by the study's focus on understanding and implementing ecological civilization principles in the CPEC context. The criteria for participant inclusion centered on their expertise and depth of knowledge in areas directly relevant to ecological civilization and sustainable development. Specifically, the target population included climate experts, scholars, researchers, academics, policymakers, industrialists, and environmentalists from China and Pakistan.

The rationale for this diverse participant pool is to ensure a comprehensive understanding of ecological civilization from multiple disciplinary perspectives. The inclusion of these groups also aligns with the study's intent to create actionable, interdisciplinary frameworks adaptable to the unique socioeconomic and environmental challenges within CPEC.

3.7. Expert profile and rationale

The expert profile was carefully curated to ensure representation across relevant domains. Table 6 and Figure 2 outline the participants' expertise, professional backgrounds, and their relevance to the study's focus on CPEC. The diverse panel was selected to ensure a balanced, interdisciplinary understanding of ecological civilization, encompassing theoretical foundations and practical applications.

4. Results

4.1. Delphi round 1

This questionnaire was analyzed using ANOVA and the responses are presented in this article. The objective of this questionnaire is to identify the key elements that will drive further investigation in the Delphi study.

Table 7 and Figures 3-5 show the ranking and impact factors of each sub-element of the main aspects. In the first aspect, the highest-ranked elements are the reconciliation of humanity and socio-environmental imbalances.

To identify the prioritized elements, ANOVA was conducted, highlighting the impact and prioritization of the elements. The ratings reflect responses to the Delphi round 1 questionnaire. Of the three main elements, all showed a significant impact on the ratings at the $p \leq 0.05$ level initially. These are:

(i) Prioritized element: Reconciliation of humanity. $p < 0.05$ for the three situations ($F(2,8) = 4.481$, $p = 0.041$)

(ii) Prioritized element: Radical environmental concerns. $p < 0.05$ for the three situations (F (2,8) = 4.938, $p = 0.041$)

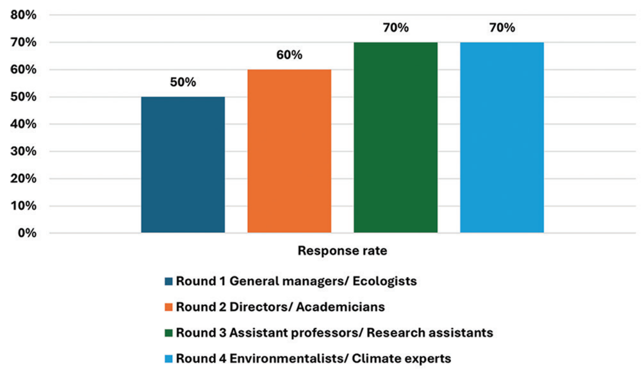

Figure 2. The expert's participation profile

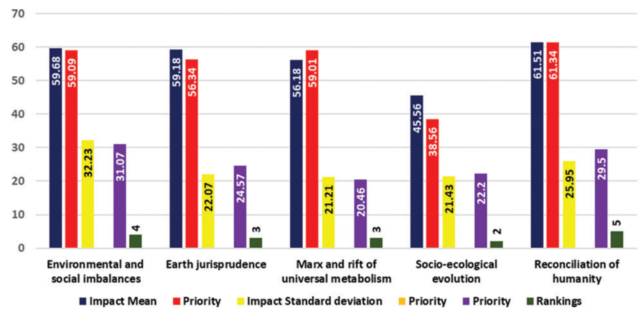

Figure 3. Visual presentation of aspect 1: Emergence of ecological civilization

(iii) Impact: Change of development mode. $p < 0.05$ for the three situations (F (2,8)= 15.845, $p = 0.003$)

(iv) Prioritized element: Change of development mode. $p < 0.05$ for the three Conditions (F (2,8) = 15.465, $p = 0.003$).

4.2. Delphi round 2

The prioritized elements from Delphi round 1 were carried over and listed in this round. Approximately 30 experts, representing various fields of study, participated in this round. NVivo software (version 14) was used to analyze the results of this open-ended, qualitative questionnaire.

Figure 6 displays the highly ranked elements, prioritized by the panel of experts in the first round. The experts come from various sectors, including environmental, industrial, research, government, and non-government sectors, reflecting a strong interest in the concept of ecological civilization, its emergence, and its possible implications for the CPEC project.

Table 8 outlines 16 elements across nine categories that can help to implement effective eco-civilization strategies in CPEC projects. All these categories are described separately.

4.3. Delphi round 3

In this round, 16 statements across nine categories were analyzed to determine their consensus level. A total of 50 experts participated, all from fields related to water,

Table 5. Delphi participants' selection criteria

Participants/experts	Selection criteria
Climate experts	To provide insights into the environmental challenges and strategies for ecological civilization.
Policymakers	Given their role in framing actionable policies under CPEC, their perspective was critical.
Academics and researchers	Scholars with expertise in sustainability studies contributed theoretical and applied insights.
Industrialists	Their participation helped address the industrial implications of ecological civilization.
Environmentalists	These stakeholders highlighted practical ecological concerns and solutions.

Abbreviation: CPEC: China–Pakistan Economic Corridor.

Table 6. Profile of the experts

Delphi rounds	Invited	Participated	Position	Experience years	Type of organization	Response rate (%)
Round 1	30	15	General managers/Ecologists	15	Government sector	50
Round 2	50	30	Directors/Academicians	10	Private sector	60
Round 3	70	50	Assistant Prof./Research assistants	10	Government sector	70
Round 4	100	70	Environmentalists/Climate experts	10	Research sector	70

Table 7. Delphi round 1 ranking

		Impact	Priority	Impact	Priority	Rankings
		Mean		Standard deviation		
Aspect 1: Emergence of ecological civilization						
1	Environmental and social imbalances	59.68	59.09	32.23	31.07	4
2	Earth jurisprudence	59.18	56.34	22.07	24.57	3
3	Marx and rift of universal metabolism	56.18	59.01	21.21	20.46	3
4	Socio-ecological evolution	45.56	38.56	21.43	22.20	2
5	Reconciliation of humanity	61.51	61.34	25.95	29.50	5
Aspect 2: Explication of the Chinese vision of eco-civilization						
1	Eco-socialism	69.65	63.92	20.43	18.61	3
2	Transcendence of Confucianism	76.74	74.00	18.14	20.38	4
3	Radical environmental concerns	71.92	71.74	24.08	26.10	5
4	Structural adjustments	66.31	62.51	20.13	23.24	2
5	Ecological redlines	69.65	63.92	20.43	18.61	4
Aspect 3: CPEC as a flagship model for ecological implications						
1	Environmental and social risks	64.83	60.92	23.16	27.75	3
2	Green development	63.51	59.84	23.97	26.15	3
3	Water eco-civilization	62.84	60.68	22.22	19.79	2
4	Change of development mode	69.68	69.26	23.14	23.93	4

Abbreviation: CPEC: China–Pakistan Economic Corridor.

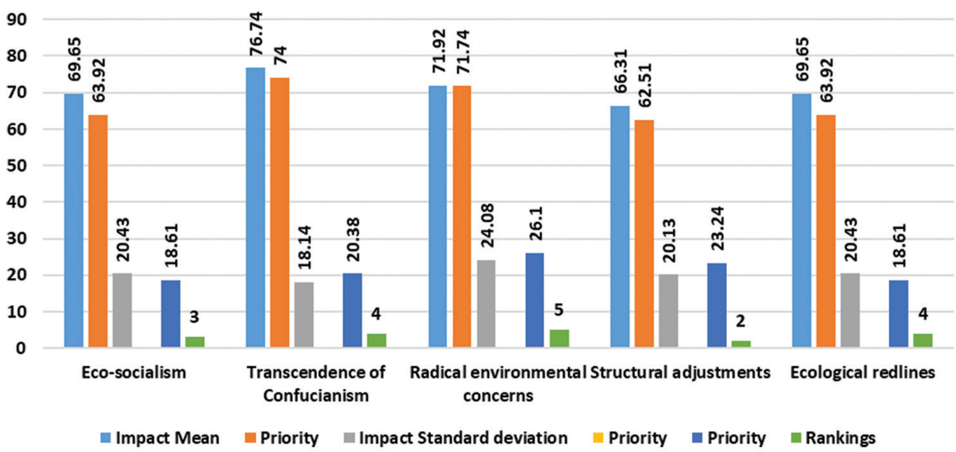

Figure 4. Visual presentation of aspect 2: Explication of the Chinese vision of eco-civilization

climate, environment, research, and other related areas. SPSS software was used for the analysis to calculate the consensus. The questionnaire for this round was closed-ended.

Cohen's Kappa is a statistical measure of inter-rater (or in the case of Delphi studies, inter-round) reliability. Table 9 shows the percentage of impact in each category, along with its consensus level. The stability of elements reflects the inter-rater reliability for the categorical items.

4.4. Delphi round 4

In this round, approximately 70 experts from related fields were selected. A priority index was created based on all responses to the survey questionnaire. The constructs or themes were ranked using a Likert scale. The scaling and coding of the questionnaire were developed and the results were analyzed quantitatively using ANOVA and SPSS software.

Table 10 presents the mean square and significance of statements among and between the expert groups.

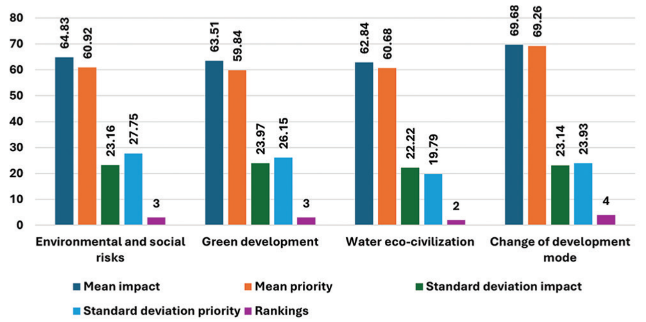

Figure 5. Visual presentation of aspect 3: CPEC as a flagship model for ecological implications
Abbreviations: STDEV: Standard deviation; CPEC: China–Pakistan Economic Corridor.

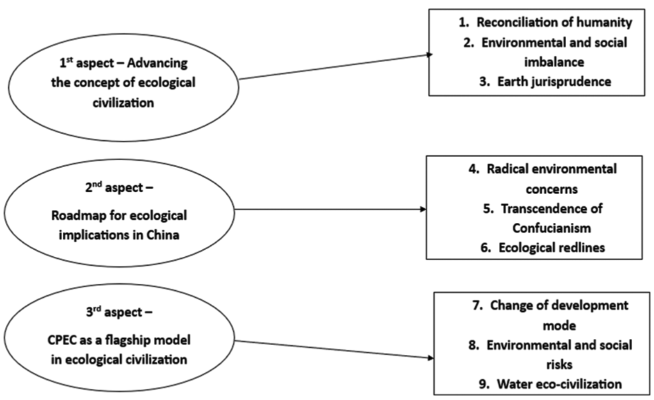

Figure 6. Delphi round 2 prioritized elements based on the results of Delphi round 1

Some experts in the participants' panel are directly from Gwadar city, providing deeper insights into the environmental situation and waste management system in the region.

Table 11 outlines the results of the final prioritized elements and consensus items. In the first theme, the sub-element most highly ranked by experts is China's struggle in formulating its environmental laws. In the second theme, two elements were ranked highest: the need for Strategic Environment Assessment (SEA) in CPEC projects and payment for eco-systems. The third theme focuses on desalination plants as an alternative water resource and a technical solution for effective water management in Gwadar. The questionnaire places significant emphasis on the CPEC project and the future challenges it poses for Gwadar city.

5. Discussion

5.1. Research outcomes

The purpose of this research was to address the research objectives and questions outlined in the study. Qualitative and quantitative approaches were used for the analysis. The results of this study are based on the Delphi technique and priority indexing system. In Table 12, the priority ranked elements in each research question are highlighted and further elaborated upon in detail.

Table 8. List of indicators and elements suggested by expert panel

Categories	Comments and suggestions
Category 1: Reconciliation of humanity	There is a need to understand emerging ideas and possibilities of the vision of eco-civilization and the purpose of the creation of the universe.
	To resolve rapidly deepening human crisis, mindsets need to be changed with the institutions that created it.
Category 2: Environmental and social imbalance	To maintain the balance between humans and the environment, human essentials and happiness must be given priority.
	A shift from imperial civilization to ecological civilization is needed, on which future life depends completely.
Category 3: Earth jurisprudence	Environmental rules and regulations need to be addressed from different dimensions to highlight climatic policy approaches and emerging future challenges.
	To regenerate the capacities of a healthy life, an essential framework is required for the spiritual and physical needs of the Earth community.
Category 4: Radical environmental concerns	Discouraging anthropocentric worldviews and values that give less regard to human beings and treat them as a world of objects.
	In the prevention and control of air, water, and soil pollution, supervision at the source, severe punishment for violations, and control throughout the process are needed.

(Cont'd..)

Table 8. ***(Continued)***

Categories	Comments and suggestions
Category 5: Transcendence of Confucianism	The humans and the natural world give rise to a spiritual and ethical system of reciprocal relationships which is important to understand.
	Understanding Confucianism to transcend the inner self and become a supreme ideal for achieving outside goals and learning moral ideals in society.
Category 6: Ecological redlines	Introducing more measurements of economic and social accomplishments that emphasize consumption, instead of conservation.
	Establishing benchmarks for ecological solutions to existing pollution problems, carbon emissions, inefficient resources, and severe environmental constraints
Category 7: Change in development mode	Demonstrating sustainability in its broadest sense to promote development mode while focusing on the quality of life and the relationship between means and purpose
	Ingenious contributions toward environmental developments, forestation more ecological zones
Category 8: Environmental and social risks	Focusing on the substantial increase of dust and airborne diseases due to the construction of industrial zones and the enhancement of volatile organic compounds in the air.
	Establishment of major functional zones, promoting technological innovations, and regulating human interferences with nature
Category 9: Water eco-civilization	Constructing new and alternative water resources and desalination plants
	Providing water resources carrying capacity by strict water resources management system and quality monitoring

Table 9. Results of Delphi round 3

Statements	Impact % by category					Consensus achieved	Stability of elements
	No impact	Low impact	Some impact	High impact	Much impact		
Category 1: Reconciliation of humanity							
How much impact do you think these statements can have in the reconciliation of humanity?							
There is a need to understand emerging ideas and possibilities of the vision of eco-civilization and the purpose of the creation of the universe	9.2	18.3	18.3	45.6	9.2	No	Almost perfect stability (1.00)
To resolve rapidly deepening human crisis, mindsets need to be changed with the institutions that created it.	-	9.2	9.2	72.8	9.2	Yes	Substantial stability (0.80)
Category 2: Environmental and social imbalance							
How much these indicators can make an impact in balancing the environmental and social factors?							
To maintain the balance between humans and the environment and human essentials and happiness must be given priority.	9.2	18.3	18.3	45.6	9.2	No	Substantial stability (0.74)
A shift from imperial civilization to ecological civilization is needed, on which future life depends completely.	-	-	45.6	45.6	9.2	No	Almost perfect stability (0.83)

(Cont'd..)

Table 9. ***(Continued)***

Statements	Impact % by category					Consensus achieved	Stability of elements
	No impact	Low impact	Some impact	High impact	Much impact		
Category 3: Earth jurisprudence							
How much these indicators can make an impact in regulating the regulations and laws of the Earth's atmosphere?							
Environmental rules and regulations need to be addressed from different dimensions to highlight climatic policy approaches and emerging future challenges.	-	-	27.4	72.8	-	No	Substantial stability (0.74)
To regenerate the capacities of a healthy life, an essential framework is required for the spiritual and physical needs of the Earth community.	-	-	36.5	54.6	9.2	No	Substantial stability (0.64)
Category 4: Radical environmental concerns							
Please select the option of how much these indicators make an impact in radical environmental patterns.							
Discouraging anthropocentric worldviews and values that give less regard to human beings and treat them as a world of objects.	-	-	18.3	63.7	18.3	Yes	Moderate stability (0.59)
In the prevention and control of air, water, and soil pollution, supervision at the source, severe punishment for violations, and control throughout the process is needed.	-	-	27.4	54.6	18.3	No	Substantial stability (0.66)
Category 5: Transcendence of Confucianism							
How much these indicators impact in the concept transcendence of Confucianism?							
The humans and the natural world give rise to a spiritual and ethical system of reciprocal relationships which is important to understand.	-	18.3	45.6	36.5	-	No	Almost perfect stability (0.85)
Understanding Confucianism to transcend the inner self and become a supreme ideal for achieving outside goals and learning moral ideals in society.	-	9.2	45.6	36.5	9.2	No	Moderate stability (0.41)
Category 6: Ecological redlines							
How ecological measurements can be made by keeping in view these indicators?							
Introducing more measurements of economic and social accomplishments that emphasize consumption, instead of conservation.	-	-	45.6	27.4	27.4	No	Moderate stability (0.48)
Establishing benchmarks for ecological solutions to existing pollution problems, carbon emissions, inefficient resources, and severe environmental constraints	-	-	45.6	36.5	18.3	No	Substantial stability (0.71)

(Cont'd..)

Table 9. ***(Continued)***

Statements	Impact % by category					Consensus achieved	Stability of elements
	No impact	Low impact	Some impact	High impact	Much impact		
Category 7: Change in development mode							
The change in development mode is the need for time to make sustainable progress and regular environmental patterns in CPEC.							
Demonstrating sustainability in its broadest sense to promote development mode while focusing on the quality of life and the relationship between means and purpose	-	9.2	18.3	54.6	18.3	No	Moderate stability (0.56)
Ingenious contributions toward environmental developments, forestation more ecological zones	-	-	18.3	45.6	36.5	yes	Almost perfect stability (0.85)
Category 8: Environmental and social risks							
How the pollution factor can be controlled in the construction and roadmaps in the CPEC project?							
Focusing on the substantial increase of dust and airborne diseases due to the construction of industrial zones and the enhancement of volatile organic compounds in air.	-	-	9.2	63.7	27.4	Yes	Almost perfect stability (0.80)
Establishment of major functional zones, promoting technological innovations, and regulating human interferences with nature	-	-	18.3	72.8	9.2	Yes	Substantial stability (0.76)
Category 9: Water eco-civilization							
In what ways, the water eco-civilization in CPEC can be effective and sustainable?							
Constructing new and alternative water resources and desalination plants	-	-	45.6	45.6	9.2	No	Almost perfect stability (0.84)
Providing water resources carrying capacity by strict water resources management system and quality monitoring	-	9.2	36.5	18.3	36.5	No	Almost perfect stability (0.87)

Abbreviation: CPEC: China–Pakistan Economic Corridor.

5.1.1. First main identified factor of the study: Ecological civilization as a Chinese concept for green development

The foremost theme identified in this study is the foundational Chinese concept of ecological civilization, which underscores the harmonious coexistence of humans and nature. This harmony, deeply rooted in China's sociocultural and philosophical traditions, is critical for sustainable development.[22] An academic scholar, from the panel of experts, commented, "What sets China's model apart is its ability to scale green development practices, combining technological innovation with traditional ecological wisdom to create a sustainable blueprint for developing nations." Ecological civilization integrates thought, order, and technology to create a framework for sustainable governance.[23] An expert in the study remarked, "The success of ecological governance in CPEC will depend on establishing clear accountability mechanisms for industries and local governments, supported by strong legal frameworks." This observation highlights the indispensable role of robust policy enforcement in fostering sustainable development.

China's progressive development of environmental laws reflects its struggle to balance industrialization with ecological preservation.[24] The study underscores that the philosophical ethos of ecological civilization aligns directly with SDG 13 (Climate Action) and SDG 15 (Life on Land), emphasizing legal and regulatory

Table 10. Analysis of variance outcomes from Delphi round 4 elements

Statements	Expert groups	Sum of squares	Df	Mean square	F	Sig.
Theme 1: Eco-civilization footprints						
1. In your opinion, the eco-socialization argument in understanding the human relation to ecosystems and ecological complexity is reflecting more in present world to which extent?	Between groups	0.016	2	0.009	0.029	0.974
	Within groups	2.168	8	0.272		
	Total	2.183	10			
2. The concept of modern capitalism depicts the great burden of pollution and disease leading to unsustainability in which communities?	Between groups	0.150	2	0.081	0.232	0.790
	Within groups	2.751	8	0.345		
	Total	2.900	10			
3. Same as capitalism, the present world system has exploited natural resources and created conflicts.	Between groups	0.516	2	0.259	0.152	0.863
	Within groups	13.668	8	1.709		
	Total	14.183	10			
4. To what extent, ecological Marxism has provided theoretical support in China?	Between groups	0.562	2	0.281	1.036	0.399
	Within groups	2.167	8	0.271		
	Total	2.728	10			
5. Ecological Marxists have to face challenges in China.	Between groups	0.221	2	0.111	0.621	0.563
	Within groups	1.418	8	0.118		
	Total	1.637	10			
6. The ecological civilization initiative in China has to have its own Chinese ecological Marxism.	Between groups	0.221	2	0.111	0.621	0.563
	Within groups	1.418	8	0.178		
	Total	1.637	10			
7. In line with China moving in the direction of ecological civilization, the following efforts are successful to what extent?	Between groups	0.016	2	0.009	0.029	0.974
	Within groups	2.168	8	0.272		
	Total	2.184	10			
8. To what extent, China is struggling to formalize environmental laws?	Between groups	0.000	2	0.565	0.470	*0.037
	Within groups	4.001	8	1.178		
	Total	4.001	10			
9. To what extent China has developed the formulation of standards for energy, water consumption, and environmental quality?	Between groups	0.221	2	0.111	0.258	0.770
	Within groups	3.418	8	0.428		
	Total	3.639	10			
10. To what extent China has progressed toward an ecological civilization system in the following areas?	Between groups	1.312	2	0.656	3.702	0.074
	Within groups	1.418	8	0.178		
	Total	2.730	10			
Theme 2: Possible implications of the Chinese vision of eco-civilization in CPEC						
11. To what extent, improvement in legalization is required to implement a comprehensive system of ecological civilization?	Between groups	0.120	2	0.065	0.214	0.813
	Within groups	2.418	8	0.303		
	Total	2.548	10			
12. Which rules under the Pakistan Environmental Protection Act (1997) need to be revised?	Between groups	0.221	2	0.111	0.621	0.563
	Within groups	1.418	8	0.178		
	Total	1.639	10			

(Cont'd..)

 doi: 10.36922/ajwep.8483

Table 10. ***(Continued)***

Statements	Expert groups	Sum of squares	Df	Mean square	F	Sig.
13. Which regulations under the Protection Act (1997) need to be revised?	Between groups	0.243	2	0.122	1.456	0.280
	Within groups	0.668	8	0.084		
	Total	0.910	10			
14. To what extent Strategic Environment Assessment is required to be part of the assessment system to implement development projects of CPEC?	Between groups	0.501	2	0.251	1.334	*0.017
	Within groups	1.501	8			
	Total	2.002	10			
16. To what extent land resource management legislation is required for securing property rights of natural resource assets in CPEC project development?	Between groups	0.243	2	0.121	0.365	0.707
	Within groups	2.668	8	0.334		
	total	2.911	10			
17. To move toward eco-civilization in CPEC, there is a need for a mechanism to carry out appropriate monitoring assessment under the following areas.	Between groups	0.312	2	0.156	0.0282	0.763
	Within groups	4.418	8			
	Total	4.730	10			
18. To what extent does the implementation of environmental taxation have to be imposed on heavily polluting industries going to be established in CPEC based on suspended solids for water pollutants, solid waste, and air pollutants (for forcing investment in cleaner technologies)?	Between groups	0.243	2	0.122	0.209	0.818
	Within groups	4.668	8	0.584		
	Total	4.900	10			
19. To what extent carbon trading would be beneficial in CPEC projects for managing ecological civilization in the following sectors?	Between groups	0.743	2	0.372	0.714	0.510
	Within groups	4.168	8	0.522		
	Total	4.911	10			
20. To what extent there is a need for systematic estimates at the national, provincial, and local levels for the maintenance of CPEC development?	Between groups	1.978	2	0.980	10.546	0.057
	Within groups	0.751	8	0.095		
	Total	2.729	10			
21. To what extent the active participation of civil society is required in environmental rehabilitation?	Between groups	1.120	2	0.565	1.323	0.310
	Within groups	3.418	8	0.428		
	Total	4.538	10			
22. To what extent do payments for ecosystem services such as fiscal incentives have to be incorporated to avoid deforestation in CPEC development?	Between groups	0.0501	2	0.251	0.572	*0.027
	Within groups	3.501	8	0.439		
	Total	4.002	10			
23. To what extent environmental governance reforms are required in environmental risk assessment agencies for development projects?	Between groups	0.120	2	0.065	0.118	0.892
	Within groups	4.418	8	0.553		
	Total	4.538	10			
24. Environmental officials have to be given rewards and punishments based on audits to take into account pollution costs and natural resource depletion in environmental risk assessment.	Between groups	0.766	2	0.384	0.897	0.447
	Within groups	3.418	8	0.428		
	Total	4.184	10			
25. To what extent, the setup for new environmental courts and experienced judges is required to encourage greener growth and curb pollution?	Between groups	0.120	2	0.064	0.213	0.813
	Within groups	2.418	8	0.302		
	Total	2.538	10			

(Cont'd..)

Table 10. ***(Continued)***

Statements	Expert groups	Sum of squares	Df	Mean square	F	Sig.
26. For promoting ecological civilization, to what extent awareness is required in the following public spheres?	Between groups	0.221	2	0.111	0.621	0.563
	Within groups	1.418	8	0.178		
	Total	1.639	10			
Theme 3: Roadmap of eco-civilization in Gwadar						
27. To what extent water supply arrangements are required in the port city?	Between groups	1.243	2	0.622	1.355	0.312
	Within groups	3.668	8	0.459		
	Total	4.911	10			
28. Ankara dam and other dams are needed to be connected to Gwadar city.	Between groups	0.016	2	0.009	0.016	0.987
	Within groups	4.168	8	0.522		
	total	4.184	10			
29. Desalination plants with Chinese investment are not viable for water because of technical issues and high operational costs.	Between groups	0.637	2	0.319	0.500	*0.011
	Within groups	5.001	8	0.626		
	Total	5.638	10			
30. To what extent the following solutions to mitigate the water crisis in Gwadar are possible?	Between groups	0.583	2	0.292	1.647	0.252
	Within groups	1.417	8	0.177		
	Total	2.000	10			
31. To what extent the construction of the East-Bay Expressway has made it difficult to make a living on fishing for the local people?	Between groups	0.561	2	0.280	0.538	0.604
	Within groups	4.167	8	0.521		
	Total	4.727	10			
32. Without treatment of industrial waste, water pollution will increase in Gwadar to what extent?	Between groups	0.129	2	0.064	0.117	0.891
	Within groups	4.417	8	0.522		
	Total	4.545	10			
33. Marine life will be in threat without proper planning of industrial development in Gwadar.	Between groups	2.242	2	1.121	1.922	0.208
	Within groups	4.667	8	0.583		
	Total	6.909	10			
34. To what extent, do the following steps have to be taken for the management of coastal pollution?	Between groups	0.220	2	0.110	0.162	0.853
	Within groups	5.417	8	0.677		
	Total	5.636	10			
35. To what extent the illegal trawling in the Gwadar waters will create an eco-civilization crisis?	Between groups	0.515	2	0.258	0.562	0.591
	Within groups	3.667	8	0.458		
	Total	4.182	10			
36. The wetland is facing threats due to CPEC developmental projects in Gwadar.	Between groups	0.515	2	0.258	0.562	0.591
	Within groups	3.667	8	0.458		
	Total	4.182	10			
37. To what extent the following factors are going to contribute to coastal erosion in Gwadar?	Between groups	0.015	2	0.008	0.028	0.973
	Within groups	2.167	8	0.271		
	Total	2.182	10			
38. The number of environmental damages can be reduced by Green GDP.	Between groups	0.432	2	0.216	0.987	0.414
	Within groups	1.750	8	0.219		
	Total	2.182	10			

(Cont'd..)

Table 10. ***(Continued)***

Statements	Expert groups	Sum of squares	Df	Mean square	F	Sig.
39. To what extent, the government can play its role in environmental governance?	Between groups	0.583	2	0.292	0.683	0.532
	Within groups	3.417	8	0.427		
	Total	4.000	10			
40. Technological ways can be used in the management of scarce natural resources, in the context of Gwadar city to what extent?	Between groups	0.159	2	0.080	0.231	*0.040
	Within groups	2.750	8	0.344		
	Total	2.909	10			
41. Reservoirs for groundwater and glaciers for freshwater resources can be stored.	Between groups	0.061	2	0.030	0.052	0.950
	Within groups	4.667	8	0.583		
	Total	4.727	10			
42. The resources of water can be reserved in the best possible way.	Between groups	0.765	2	0.383	0.325	0.732
	Within groups	9.417	8	1.177		
	Total	10.182	10			
43. Foreseeable water pollution can be reduced to protect the ecological environment in Gwadar city, within the context of CPEC.	Between groups	1.129	2	0.564	1.322	0.319
	Within day	3.417	8	0.427		
	Total	4.545	10			

Note: *Indicates statistically significant elements in all the three themes at $p \leq 0.05$.
Abbreviations: DF: Degrees of freedom; CPEC: China–Pakistan Economic Corridor; GDP: Gross domestic product; Sig.: Significance.

Table 11. Outcomes of final prioritized and consensus elements from Delphi study

Statement	Consensus level (%)	Mean	Rank	Significance	Stability
1. To what extent, China is struggling to formalize environmental laws; A. Improved compatibility in environmental related laws B. Revision of existing laws C. Improvement in legislation D. Any other	81.8	4.00	6–8	0.037	Moderate stability (0.48)
2. To what extent Strategic Environment Assessment is required to be the part of assessment system to implement development projects of CPEC	90.9	4.00	8–10	0.017	Moderate stability (0.59)
3. To what extent payments for ecosystems services such as fiscal incentives have to be incorporated to avoid deforestation in CPEC development	81.8	4.18	6–8	0.027	Almost perfect stability (0.86)
4. Desalination plants with Chinese investment are not viable for water because of technical issues and high operational costs	90.9	4.27	8–10	0.011	Almost perfect stability (0.85)
5. Technological ways can be used in management of scarce natural resources, in context to Gwadar city to what extent	90.9	3.91	8–10	0.040	Slight stability (0.12)

Abbreviation: CPEC: China–Pakistan Economic Corridor.

structures that prioritize ecological harmony. One of the climate experts commenting on the global significance of China's steps said, "What sets China's model apart is its ability to scale green development practices, combining technological innovation with traditional ecological wisdom to create a sustainable blueprint for developing

Table 12. Priority ranking

Themes	Priority ranked elements
1st research question: Eco-civilization footprints	China's struggle in formulizing environmental laws
2nd research question: Possible implications of the Chinese vision of eco-civilization steps in CPEC	Requirement of Strategic Environmental Assessment system in CPEC projects
	Steps for eco-system services and avoid deforestation
3rd research question: Roadmap for water eco-civilization	Alternative water resources in the areas near CPEC, e.g., desalination plants
	Technological ways for management of scarce natural resources in residential areas around CPEC projects.

Abbreviation: CPEC: China–Pakistan Economic Corridor.

nations." The conceptual framework of ecological civilization as a guiding principle illustrates how thought leadership can drive technological advancements and institutional governance to build a sustainable future.[25]

5.1.2. Second main identified factor of the study: Ecological civilization and the China–Pakistan Economic Corridor

The second theme focuses on integrating ecological civilization principles within the CPEC, a flagship project of the BRI. One of the environmental consultants highlighted, "CPEC provides a unique opportunity to implement China's ecological civilization principles beyond its borders. By embedding sustainability in infrastructure projects, CPEC can serve as a testbed for replicable green development practices in other regions." Two critical elements emerged as priorities in this theme: the implementation of a SEA system and the urgent need for ecosystem services to counteract deforestation. In the words of a policy analyst, "The ecological dimension of CPEC must go beyond compliance to embrace proactive green policies, such as integrating renewable energy solutions into urban planning and ensuring water resource sustainability in project zones." According to analysts and environmentalists, the ecological stakes of CPEC demand adherence to international best practices to ensure long-term sustainability. A policymaker emphasized, "CPEC has the potential to be a global model for green infrastructure, but this requires adopting international best practices and ensuring that all stakeholders are committed to sustainability."

The research underscores the necessity of SEA systems to integrate environmental considerations into policymaking, particularly for large-scale infrastructure projects like CPEC. In addition, ecosystem services, such as afforestation and soil conservation, are essential to offset environmental degradation.[26] These priorities are directly linked to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), highlighting the importance of aligning large-scale development with ecological sustainability. As an industrialist from the experts' panel commented, "Ecological civilization in the context of CPEC can bridge infrastructure development with environmental goals. Projects like green transportation corridors and renewable energy plants within CPEC show promising alignment with SDG targets." These findings indicate that CPEC must institutionalize these strategies to transition from an industrial project to an environmentally conscious initiative.

5.1.3. Third main identified factor of the study: Water eco-civilization roadmap

The third theme addresses the critical issue of water resource management in areas near CPEC. Two key elements identified by experts include the development of alternative water resources and the adoption of advanced technological solutions for water management. In the words of an environmentalist, "Water ecological civilization requires immediate action, such as desalination plants powered by renewable energy, to secure the water supply while minimizing ecological disruption." The study emphasizes the potential role of desalination plants in addressing water scarcity, although experts caution that population growth and intensified development activities necessitate more comprehensive strategies. Another environmentalist noted, "Policy frameworks must include local community voices to balance ecological preservation with socioeconomic development. Without inclusivity, even the best-laid plans are likely to fail." This perspective underscores the importance of participatory governance and community engagement in ensuring the success of water management initiatives.

The study aligns water resource management strategies with SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities). It highlights the importance of integrating community-centric approaches with technological innovations, such as water recycling and efficient distribution systems. Furthermore, the findings reveal a pressing need for policy frameworks that address water scarcity and mitigate pollution caused by industrial and infrastructural expansion within CPEC regions. Experts from the CPEC Center stressed the urgency of creating a sustainable water management plan, linking it with broader ecological goals to avoid long-term environmental degradation.

5.2. Practical implications

The CPEC presents opportunities and challenges in balancing economic growth with environmental sustainability. To address these challenges, several strategic measures can be implemented to ensure that CPEC aligns with global sustainable development goals while mitigating its ecological footprint. The measures include:

(i) Implementing SEA: Policymakers should institutionalize SEA systems for all CPEC projects to systematically evaluate environmental impacts at every stage of development. This ensures compliance with international sustainability standards and promotes proactive environmental governance, aligning with SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production).[27]

(ii) Developing a water resource management framework: The study highlights the need for alternative water resources and advanced water management technologies, such as desalination plants and recycling systems, particularly in Gwadar. Planners should create integrated frameworks addressing water scarcity and pollution. Both of these align with SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities).[28]

(iii) Adopting ecosystem services and reforestation strategies: To counteract deforestation and enhance ecosystem services, policies should prioritize large-scale afforestation and soil conservation projects along CPEC routes. This would mitigate ecological damage, preserve biodiversity, and contribute to SDG 15 (Life on Land).[29]

(iv) Institutionalizing participatory governance models: Engaging local communities and stakeholders ensures inclusivity and sustainable implementation. Policymakers should integrate community voices into decision-making processes to balance ecological preservation with socioeconomic needs. It will help in reinforcing SDG 10 (Reduced Inequalities) and SDG 16 (Peace, Justice, and Strong Institutions).[30]

(v) Creating bilateral green governance frameworks: China and Pakistan can collaboratively develop a CPEC Green Agreement, focusing on shared ecological goals, carbon reduction targets, and biodiversity conservation. This joint governance model strengthens international cooperation and ensures long-term environmental sustainability.[31]

6. Conclusion

The study participants came from various sectors, including government, non-government organizations, education, industry, CPEC, the economic and social sectors, the planning commission, water and environment sectors, and policymakers. The collaboration among these experts and scholars was a great phenomenon, as it fostered rich discussions and sharing of valuable insights during the brainstorming sessions. This collaboration played a crucial role in developing a valuable questionnaire. Moreover, the results of the questionnaire highlighted the diverse views of all the participants and their mutual agreement on key issues. The majority of experts concluded that ecological civilization could serve as a successful model in CPEC and green development. The collaboration between government officials and industrialists highlighted various environmental challenges and potential solutions. It was mutually agreed that ecological civilization should be emphasized as a key concept for green development in education, at both primary and higher levels, to ensure it becomes widely understood and not an unfamiliar concept to the public.

A key limitation of this study is the potential bias introduced by the selection of experts. Although the panel was diverse, it may not fully capture all perspectives across different regions and disciplines. The reliance on a panel primarily composed of participants with academic, policy, and industrial expertise may inadvertently exclude grassroots voices and local community insights, which are critical to understanding the socio-environmental nuances of CPEC projects. Furthermore, the geographic focus on specific areas like Gwadar and broader CPEC zones may limit the generalizability of findings to other regions facing similar ecological challenges. These factors underscore the need for a more inclusive and representative approach in future research, ensuring a holistic understanding of ecological governance.

Future research could address these limitations by adopting longitudinal studies that examine the sustained impacts of ecological civilization initiatives within CPEC over time. Such studies could assess how policies evolve, their effectiveness in mitigating environmental degradation, and their contributions to SDGs like Climate Action (SDG 13) and Clean Water and Sanitation (SDG 6). In addition, comparative studies between CPEC and other BRI projects would provide valuable insights into the best practices and challenges in implementing ecological civilization across diverse sociopolitical contexts. This would further refine strategies for achieving environmentally sustainable development in Pakistan, China, and beyond.

Acknowledgments

The completion of this research paper would not have been possible without the support of participants in this Delphi technique. Their contributions and overwhelming attitude toward completion of this paper for completing this research paper. The encouragement and insightful feedback were instrumental in accomplishing this paper.

Funding

None.

Conflict of interest

The authors have no conflicts of interest or any financial interest, or non-financial interest.

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Availability of data

The data supporting the findings of this study are available upon reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 22-32.
doi: 10.36922/ajwep.7337

ORIGINAL RESEARCH ARTICLE

A comprehensive study on municipal solid waste management practices in Jamshedpur City, India

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Received: December 11, 2024; Revised: February 17, 2025; Accepted: February 20, 2025; Published Online: March 5, 2025

Abstract: In developing nations such as India, managing municipal solid waste (MSW) presents a substantial challenge, with around 90% of MSW disposed of in open dumps and unregulated landfills. This improper waste disposal poses serious health risks to nearby communities. This study delves into MSW's characteristics, separation, collection, transportation, and disposal techniques in Jamshedpur, India. Information was gathered through personal visits, interviews, and official records from the Municipal Corporation and Jamshedpur Utility Service Company Pvt. Ltd., currently known as Tata Steel Utilities and Infrastructure Services Limited (TSUISL), a subsidiary of Tata Enterprise. TSUISL manages municipal services and efficiently handles waste management tasks such as collection, storage, transportation, and processing. Techniques such as composting and bio-methanation convert waste into valuable resources, reducing landfill pressure. This study aims to understand the MSW management framework implemented by TSUISL and provide practical recommendations to enhance the city's existing waste management system.

Keywords: Tata Steel Utilities and Infrastructure Services Limited; Municipal solid waste; Municipal solid waste management; Treatment; Organic waste

1. Introduction

Solid waste encompasses many materials, including solid, liquid, semi-solid, and even gaseous substances. Solid waste comprises several kinds of waste products, including trash, wastewater treatment plant refuse-sludge, and other matters thrown away. Various human activities produce solid waste, including mining, agriculture, urbanization, industry, and commerce. Residential houses, institutional buildings, and commercial establishments produce municipal solid waste (MSW). Households often dispose of a wide range of items, including food waste, paper, plastic, glass, metal, cans, garden clippings, and other materials. The composition of MSW can vary depending on various factors, such as the type of area (residential or commercial), cultural practices, and the economic status of the nation (ranging from low-income to high-income states).[1] The waste produced by higher-income individuals tends to be more diverse and intricate due to their elevated living standards and evolving dietary preferences. Studies have shown that higher income levels correlate with increased waste production, with metropolitan areas generating more waste than smaller towns.[2] The rapid growth of urban populations puts a strain on the current infrastructure, necessitating additional resources to uphold the same level of MSW management. MSW has become a burning concern in metropolitan areas and urban towns. Central Pollution Control Board (CPCB) has observed a significant rise in the amount of MSW, with an increase of 77.12 million tonnes between 2000 and 2005. In 2020, India achieved the status of an industrialized nation. However, a concerning issue remains: 90% of wastes are improperly disposed of in open dumps and unmanaged landfills.[3,4]

Tata Steel Utilities and Infrastructure Services Limited (TSUISL), a well-known Indian private company under Tata Enterprises, is dedicated to providing a range of urban infrastructure services that contribute to the betterment of the community. To provide sustainable solutions with major advantages, TSUISL works in partnership with urban local governments, businesses, associations, communities, and individuals. Water supply, power distribution, structural and civil construction, and MSW management are all included in their services. Waste transportation, trash sorting, composting, drain and street cleaning, waste disposal, and waste transportation to landfills or dumpsites are all handled by TSUISL's Public Health & Horticulture Services (PH & HS) division.

Efficient management of MSW aims to minimize the environmental impact caused by waste. The process involves gathering, sorting, moving, processing, and removing solid waste from cities.[5] The study has several objectives: to evaluate the operational framework of TSUISL, to determine waste composition, collection, and treatment efficiency in Jamshedpur city, and to identify existing gaps in MSW management for proposing actionable recommendations for establishing circularity in public–private partnership model. Through a systematic approach, primary and secondary data were gathered from the command area for the study of Jamshedpur's MSW management. The study investigated many facets of waste management, encompassing generation, collection, segregation, transportation, treatment, and disposal. Waste samples were collected from different areas in the commercial zones of Jamshedpur, ensuring they were mixed thoroughly for consistency. Based on their physical composition, the samples were divided into groups including paper, plastics, glass, leather, wood, metal, thermocol, textiles, and organic fractions.[6] The organic fraction, which consisted of vegetable peels, food waste, and garden debris, was carefully sorted and measured to determine its proportion in the overall sample, along with the non-biodegradable components.[7]

In addition, the study included conducting interviews with individuals and making direct inquiries about the generation, handling, and disposal of MSW. Secondary data were collected by consulting municipal authorities, i.e., particularly TSUISL, and reviewing relevant online sources. This comprehensive approach provided a thorough analysis of Jamshedpur's MSW management practices, providing valuable insights into the region's waste composition and handling methods.

Ultimately, the combination of Jamshedpur's rich history, thriving industries, and stunning natural surroundings positions it as a prime destination for exploring urban planning and environmental management.[8] The role of TSUISL in managing the city's municipal services, particularly solid waste management, showcases the success of public–private partnerships in tackling urban challenges. The in-depth examination of Jamshedpur's waste management practices offers a blueprint for other cities aiming to harmonize industrial development with ecological sustainability.

2. Literature review

India has a population of over 1.42 billion, making it the second-largest and most populous country globally. It accounts for a significant 17.6% of the global population. According to data from the World Bank in 2014, urban areas are home to 32% of the population, whereas the remaining 68% reside in rural areas.[9] In India, the urban population is experiencing a rapid growth rate of 3.35%/year. From 1951 to 2011, there was a significant increase in the proportion of individuals residing in urban areas, rising from 17.35% to 31.2%, according to the census conducted in 2011.[10] Managing MSW is a burning issue that has garnered global attention. The rapid urbanization, urban growth, and economic development in Indian cities have led to significant changes in their physical size and put additional pressure on infrastructure services.[11]

According to the CPCB (2018), a staggering amount of municipal garbage is being produced daily due to various activities such as household, industrial, agricultural, institutional, and commercial. MSW composition can differ significantly depending on several factors, including socioeconomic status, climate, culture, customs, and dietary preferences of individuals.[12] An efficient system for collecting, transporting, and disposing of such a large amount of solid waste is crucial. It also requires a good understanding of waste characteristics, proper collection and disposal methods, and the potential for recycling and energy generation.[13] Based on wet weight analysis, a significant portion of MSW at generation sources and collection sites consists of organic matter (40 – 60%), ash and fine earth (30 – 40%), paper (3 – 6%), and minimal amounts of plastic, glass, and metals (<1% each). The lower calorific value varies from 800 to 1000 kcal/kg, and the carbon to nitrogen (C/N) ratio falls to the range of 20 – 30%.[14] According to Grazhdani,[15] waste management efficiency has become increasingly critical due to urbanization and industrialization, which have led to a linear consumption approach. This approach results in resource shortages and environmental degradation. Sustainable development in waste management means using waste as a resource, which is essential. The EU's Waste Framework Directive ranks waste treatment activities by environmental impact, promoting waste prevention in the order of reuse, recycling, and energy recovery.[16]

Harmonized waste management legislation defines the responsibilities of stakeholders, including governments, municipalities, and producers.[17,18] Citizens play a key role in separating household waste for recycling, which is crucial for the circular economy.[19] Effective waste management requires tailored strategies and active citizen participation.[20] According to Zhu *et al.*,[21] successful MSW management systems are known for these characteristics: effective allocation of resources, integration with advanced technology, and establishment of robust policy frameworks. Everyday items discarded by the public, such as household, commercial, and institutional wastes, fall into the MSW category. The management of MSW involves a series of processes including generation, collection, transportation, treatment, and disposal.[22,23]

In developing countries, the issue of MSW management is made worse by the fast-paced urbanization, increasing population, and limited financial resources. Often, improper infrastructure and formal waste management systems result in subpar waste disposal methods, such as open dumping and burning. These practices bring about considerable environmental and health hazards, as highlighted.[24] Many prior studies have attempted to address the challenges of MSW management in metropolitan cities such as Delhi and Mumbai, while exploration of public–private partnership model in tier-2 city like Jamshedpur, where industrial collaboration plays a key role in waste management, remains critically limited. There is less focus on the socioeconomic factors influencing segregation behaviors in residential and commercial zones, which significantly impact waste management efficiency. Thus, the current study aims to bridge the gap by analyzing Jamshedpur's public–private partnership framework (TSUISL), waste characterization of commercial zones, and potential disposal strategies.

3. Materials and methods

3.1. Study area

Jamshedpur lies on the Chota Nagpur Plateau at latitude 22.47°N and longitude 86.12°E, within the East Singhbhum district of Jharkhand, India. The picturesque Dalma Hills surround the city, while the Subarnarekha and Kharkhai rivers cross it, enhancing its natural beauty and ecological significance. Known as the "Steel City," Jamshedpur is renowned as the home of Tata Steel, India's first privately owned iron and steel company. It was founded by Jamsetji Nusserwanji Tata. The city covers an area of 64 sq km and was given the name Jamshedpur in 1919 by Lord Chelmsford as a tribute to its forward-thinking founder.[8]

Based on the 2011 census data, the population of Jamshedpur was 725,623, while the Jamshedpur Urban Agglomeration had 1,337,131 residents. The administrative structure of Jamshedpur is quite intricate, with various bodies responsible for its functioning. These include the Adityapur Municipal Council, Jamshedpur Notified Area Committee, Mango Notified Area Committee, Jugsalai Municipality, TSUISL Area, and Gamharia Nagar Panchayat. The Jamshedpur Notified Area Committee (JNAC) is in charge of the Tata lease area, also called the command area, and the non-lease area. TSUISL oversees municipal services within the 41 km^2 command area, while the JNAC manages the rest of the city (Figure 1).[8]

Jamshedpur is known for being India's first planned city, a legacy from the early 20th century. The city's planning and development have played a crucial role in maintaining a harmonious balance between industrial growth and environmental sustainability. Jamshedpur has a tropical wet and dry climate, with an average annual rainfall of 1,236 mm and temperatures ranging from a scorching maximum of 43°C in summer to a chilly minimum of 6.6°C in winter. Due to its distinct climate, geographical features, and industrial activities, Jamshedpur is an essential location for urban planning, industrial ecology, and environmental management research.[25]

TSUISL, a prominent Indian private company under Tata Enterprises, excels in delivering various urban infrastructure services to improve community

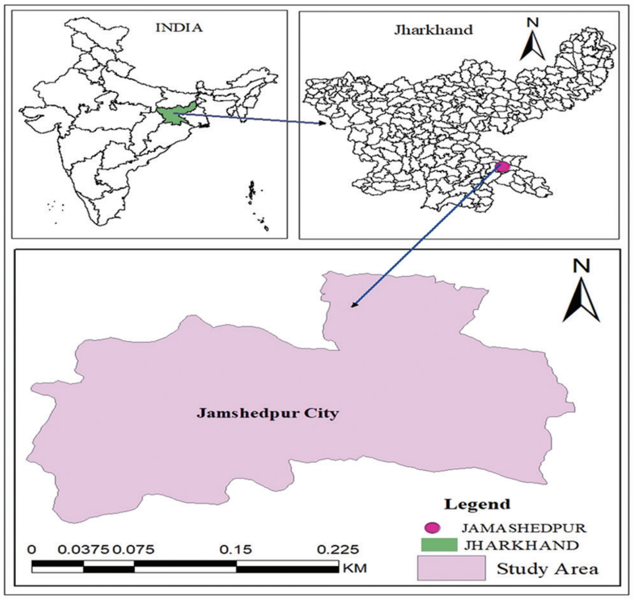

Figure 1. Study area (Jamshedpur)

well-being. TSUISL collaborates with urban local bodies, industries, civic groups, individuals, and communities to offer sustainable solutions with significant benefits. Their services encompass MSW management, water supply, power distribution, and structural and civil construction.[26] TSUSIL's PH & HS division manages MSW management. This division handles waste disposal, drain and street cleaning, waste transportation, trash sorting, composting, and transporting waste to landfills or dumpsites.

3.2. Methods and methodology

The study utilized a comprehensive approach to gathering primary and secondary data on MSW management in the command area of Jamshedpur. The research examined different aspects of waste management, encompassing generation, collection, segregation, transportation, treatment, and disposal (Figure 2).

We gathered waste samples over 6 months, from February to August 2023, considering seasonal variation from various collection points of residential and commercial zones of the Jamshedpur command area. We carefully mixed the waste samples to achieve uniformity and obtained representative samples using the quartering and coning methods.[27]

3.2.1. Selection of representative sample

The quartering and coning method is a sampling technique often used to acquire a representative sample of waste from an unprocessed MSW following ASTM D5231-92 standard.[27] We sorted the samples into categories based on their physical composition: paper, plastics, glass, leather, wood, metal, thermocol, textiles, and organic fractions. They meticulously sorted and measured the organic fraction of vegetable peels, food waste, and garden debris to determine its percentage in the overall sample. They also classified and quantified the non-biodegradable components.

To enhance the data collected, we conducted interviews with 120 citizens, among them 60 individuals were from the residential zone while the remaining 60 were from the commercial zone, which is the major contributor to MSW in Jamshedpur. We conducted direct inquiries with 10 staff members of TSUISL and field visits to collect data on the generation, handling, and disposal of MSW. We obtained secondary data by consulting with municipal authorities, specifically by TSUISL, and reviewing relevant online sources. This extensive approach allowed for a detailed examination of Jamshedpur's MSW management practices, offering valuable observations on the area's composition and handling of waste.

4. Results and discussion

4.1. Waste characterization

MSW composition can differ significantly depending on several factors, including socioeconomic status, climate, culture, customs, and dietary preferences of individuals. The carbon to nitrogen (C/N) ratio is approximately 26 ± 5% in cities with a population of <0.1 – 0.5 million. The compostable fraction varies between 29% and 63%, with recyclables accounting for 13% – 36%. These cities also have a significant calorific value on a dry basis, ranging from 590 to 4000 kcal. The garbage generated in Jamshedpur can be divided into three categories: recyclable, non-recyclable, and inert. As shown in Figure 3, the total waste comprises compostable materials, accounting for approximately 38 – 40%. On the other hand, the percentage of recyclable waste ranges from 18% to 22%. A portion of the remaining waste, about 33 – 38%, is made up of non-recyclable or inert materials (Table 1). In addition, there has been an apparent decline in the sorting of recyclable wastes such as paper, plastic, and glass by individuals at the collection points.[28]

4.2. MSW generation

This case study was conducted in a vibrant commercial area, with a residential colony near the Kadma market in Jamshedpur. In the TSUISL command area, a community bin gathers household rubbish. Kadma market features diverse shops catering to various needs, including fresh produce, everyday essentials, clothing, office supplies,

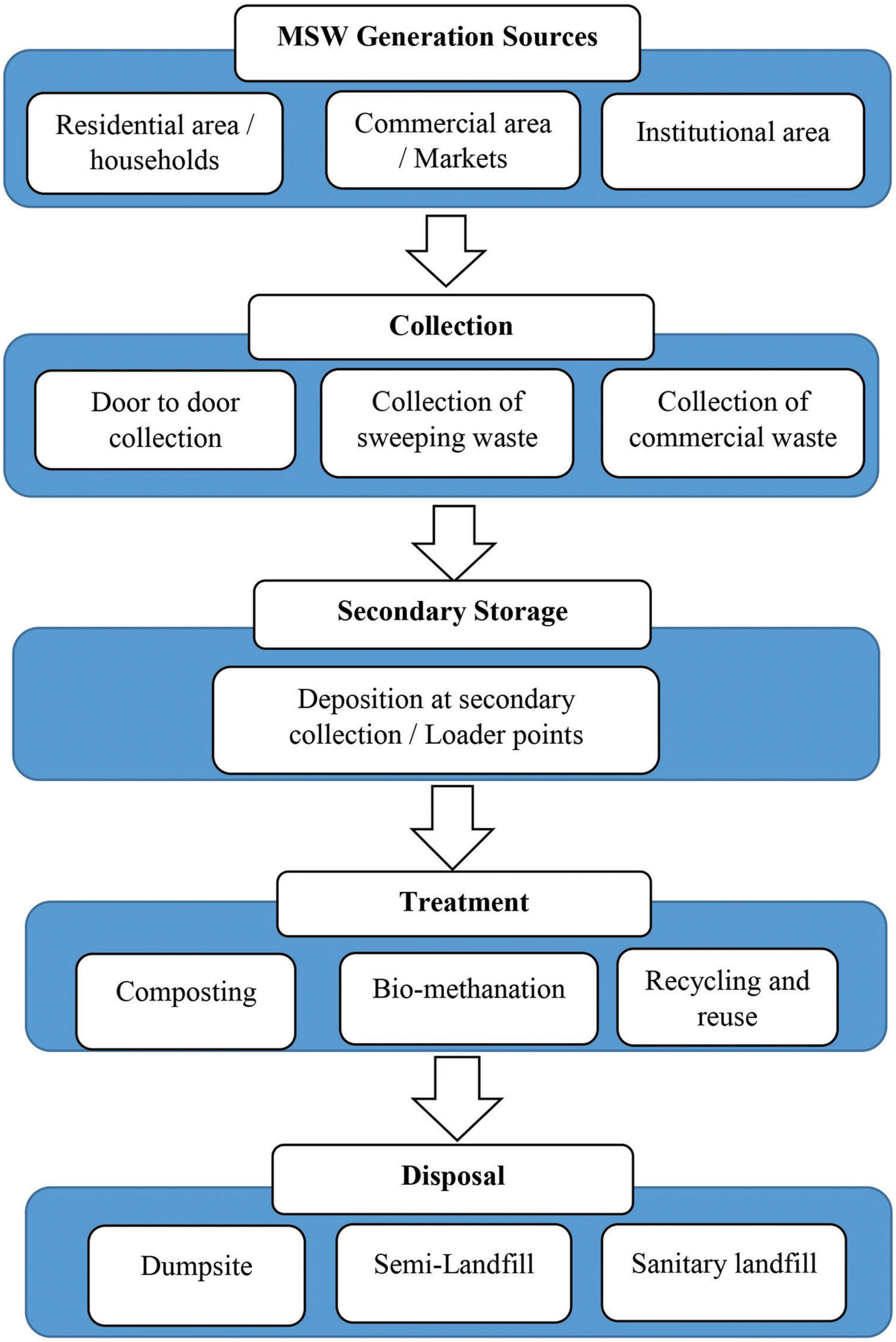

Figure 2. Flowchart of municipal solid waste management in Jamshedpur

accommodations, health care, and electronics. These facilities produce a wide variety of trash, such as biological waste, e-waste, and MSW. Jamshedpur generates about 400 tonnes of garbage every day, or 0.52 kg/person (Jamshedpur Utility Service Company Pvt. Ltd.[1] 2021).

[1] JUSCO, *Annual Diary* (Jamshedpur: JUSCO, 2022), 28.

4.2.1. Primary collection

TSUISL is responsible for managing the daily collection of waste from different areas of Jamshedpur. TSUISL employs a diverse range of workers to handle tasks such as street sweeping, waste collection, drain cleaning, and transportation, among other responsibilities. TSUISL has introduced a variety of community bin types, including hanging bins, masonry bins, residential pipe bins, dumper buckets, and garbage collectors as shown in Figure 4. A study conducted by the National Environmental Engineering Institute, Nagpur, reveals that Jamshedpur has enough workforce per 1000 individuals in its population as per guidelines.[29]

Strategically positioned community bins enable residents to conveniently dispose of their waste. This strategy is highly efficient and commonly implemented in numerous Western countries. The bins need to be closed, esthetically pleasing, clean, easy to use, and have distinct sections for paper, recyclables, mixed debris, and biodegradable waste for them to be widely acceptable.

(i) Door-to-door collection: When the waste collector arrives at the scheduled hour, the rubbish is left at the doorstep. This waste collection method is more compatible with human behavior, as it is extremely convenient for the homeowners, except that they need to be cooperative by getting the rubbish ready at the scheduled collection hour. Most of the waste collections, up to 75%, are conducted using this method

(ii) Community bin collection: The vehicles arrive at a specific location on a designated day and time to collect household waste. Households can easily dispose of their waste by simply emptying it into the vehicle. The success of this strategy lies in public engagement and the cooperation of homeowners in attending the planned service appointments. Approximately 20% of waste collections are conducted through this method

(iii) Curbside collection: On waste collection day, homeowners must set out the containers at the curb. After that, they must put the empty containers back where they were stored until the next collection. The remaining 5% of waste collections happen through this method.

4.2.2. Transfer station or secondary storage site

These loader points serve as secondary storage stations where the tripper accumulates the primary waste collected. The primary collection in narrow lanes is mostly done by tricycle or handcart. Once the site is fully filled with collected waste, workers load it into a heavy vehicle like a dumper or compactor. They then send these loaded vehicles to treatment or processing stations located in Bara Dih and the surrounding areas of Jubilee Park. Sometimes, they also carry out segregation activities to sort biodegradable, non-biodegradable, and recyclable materials. TSUISL operates at multiple

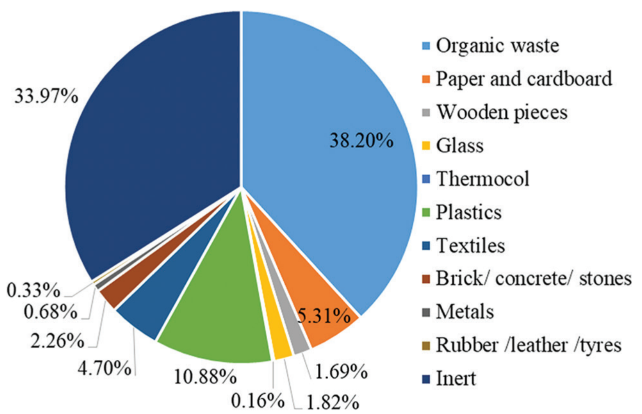

Figure 3. Composition of municipal solid waste in Jamshedpur

Table 1. Comparison of MSW composition of Jamshedpur and other Indian cities

MSW composition	Jamshedpur average (%)	Indian cities average (%)
Organic	38 – 40	40 – 60
Recyclable	18 – 22	13 – 36
Inert	33 – 38	30 – 40

Abbreviation: MSW: Municipal solid waste.

Figure 4. Different types of community bins are placed at Kadma Market, Jamshedpur. (A) Dumper bucket at residential area, Kadma. (B) Masonry bins at a vegetable market, Kadma.

Table 2. Street sweeping calculation

Parameter	Value	Remarks
Sweeping coverage per person	250 m/day	136+50+32=218
Minimum pay per sweeper	₹136/day ($1.62*)	
Other allowances	₹50/day ($0.60*)	
Safety gear cost	₹32/day ($0.40*)	
Overall cost per person	₹218/day ($2.60*)	

Note: *Refer to footnote.[2]

loader points, including the ones in Sonari and Ramdas Bhatta.

4.2.2.1. Transportation expenses

For street sweeping per kilometer, TSUISL spent ₹872 daily/$10.40 (Table 2).

The main costs of primary collection include labor and utilities, such as fuel, vehicle, leakage, and maintenance.

A tripper covers over 2000 households and requires two workforces to operate. Each tripper has a maximum carrying capacity of 1.5 tonnes. The total waste generated by households amounts to 5.2 tonnes, which requires 3.4 trips for removal. The total distance a tripper travels is 52 km daily with a fuel consumption of 2.6 L at ₹90/L ($1.10/L), costing ₹234. The wages of the workforce involved is ₹336. The total cost involved in waste collection encompasses the wages of workers, the cost of fuel used, and the expenses for utilities (safety gear like gloves, masks, *etc.*) provided, which cost ₹602/day ($7.202). Thus, the cost of collection per tonne is ₹115.80 or ₹116 ($1.40[2]) (Tables 3-5).

[2] Exchange rate: 1 USD ≈ ₹ 84 (2024 average).

4.2.3. Segregation and sorting

The workers employed by TSUISL at the secondary collection site are responsible for segregating and sorting mixed wastes received into biodegradables, non-biodegradables, and recyclables.[29] The recovery process entails laborious segregation of plastic materials and some metal and other recyclable elements. The segregated plastic is meticulously cleansed and arranged for storage at the Ramdas Bhatta depot. Using plastic in road making will guarantee that it may be effectively recycled in the future and utilized in the fabrication of plastic roadways. The recovered valuable metal might be sold as scrap or moved to production or recycling facilities.[30] The problem of segregation at the source persists due to a lack of awareness and a reluctance to address the issue. Implementing effective waste segregation practices enhances treatment efficiency and minimizes the requirement for unnecessary disposal.[30] Furthermore, several individuals found scavenging at the dump site. In addition, they play a crucial role in trash sorting in developing nations such as India.

Table 3. Cost estimation for door-to-door collection

Parameter	Value	Remarks
Coverage	2000 households in 8 h	
Distance from HH to loader point*	15 km	
Diesel mileage	20 km/L	
Personnel required	2 (driver, helper)	
Per-capita waste generation rate	2.6 kg/household	
Total waste generated (2000 HH)	5.2 tonnes	2.6×2 000=52000
Tripper capacity	1.5 tonnes/trip	
Number of trips required	3.47 trips	5.2/1.5=3.466
Distance covered by tripper	52 km	15×3.4=51
Diesel required	2.6 L	52/20=2.6
Diesel cost	₹90/L ($1.10*)	
Total fuel cost	₹234 ($2.80*)	90×2.6=234
Driver wage	₹200/day ($2.40*)	
Helper wage	₹136/day ($1.60*)	
Total workforce cost	₹336/day ($4.00*)	200+136=336
Cost of utility (safety gears)/day	₹32 ($0.40*)	
Total cost of collection	₹602/day ($7.20*)	336+234+32=602
Cost of collection per tonne	₹116 ($1.40*)	602/5.2=115.76

Notes: Thus, cost per tonne of waste pickup=Total cost/Total waste generated, i.e., 602/5.2=₹116 ($1.40*). *Refer to footnote[2].
Abbreviation: HH: Households.

4.2.4. Processing/treatment

The mixed waste includes non-biodegradable and hazardous materials that pose a risk to health or the environment. By eliminating these components, we convert waste into valuable assets. We can also convert waste materials' biodegradable or organic components into beneficial organic compost.[31]

Windrow composting is extensively utilized on a significant scale in India due to the arid climatic conditions. Composting with open triangular or trapezoidal windrows is more favorable in warmer climates. In windrow composting, organic materials decompose to create stable organic matter.[32] This process involves carefully controlling the temperature and microbiological activity to break down organic materials into a stable, nutrient-rich substance. People widely utilize compost in various fields, such as agriculture, horticulture, home gardening, land reclamation, wetland mitigation, and erosion prevention. Its primary purpose is to enhance soil organic matter and create an optimal environment for plant growth.[33] These materials have a high moisture content, which makes them appropriate for anaerobic digestion and biogas production.

As shown in Figure 5, TSUISL installed a windrow composting facility with a 50 – 60 TDP capacity in Jamshedpur. This plant is in Sakchi, next to Jubilee Park. The success of the windrow composting technique requires multiple favorable conditions, with one of them being a hot and humid climate. Recently, a bio-methanation facility with an anaerobic digester capacity of 20 MLD was established, and plastic waste has become increasingly popular for road construction, which is widely recognized as a highly efficient way to extract value.[34]

4.2.5. Landfill/dumpsite

In India, landfills and dumpsites serve different meanings for the waste disposal mechanism. Unregulated waste disposal sites, i.e., dumpsites, are for open disposal of waste without safeguarding regulations. These dump sites are mostly depression areas, barren areas, or unclaimed land near any water bodies. The landfill is a technical term for regulated disposal sites with properly engineered facilities for liners, leachate collection, and methane capture mechanisms to ensure the safety of people and the environment (Table 6). Dumpsites are prevalent because of inadequate infrastructure, financial constraints, and non-compliance with scientific management practices.[35]

(i) Jamshedpur also has a dump site in Bagaun Hathu

(ii) A sophisticated method for preventing environmental pollution is through compacting waste and adding topsoil cover in a semi-controlled/operated landfill. Jamshedpur has a semi-controlled landfill/dumpsite beside the XLRI educational group on Marine Drive highway

Table 4. Tricycle collection

Parameter	Value	Remark
Coverage	800 households daily	Manual tricycle is a semi-mechanical vehicle operated by manpower specifically in narrow lanes. They operate to cover a maximum of 800 HH for waste collection[27]
Per-capita waste generation rate	2.6 kg/household	
Total waste generated (800 HH)	2.08 tonnes	

Abbreviation: HH: Households.

Table 5. Hand cart/trolley collection

Parameter	Value	Remark
Coverage	200 households daily	Handcart is operated by workers, specifically in narrow lanes. They operate to cover a maximum of 200 HH for waste collection.
Per-capita waste generation rate	2.6 kg/household	
Total waste generated (200 HH)	0.52 tonnes	

Abbreviation: HH: Households.

Table 6. Comparison of dumpsites versus sanitary landfills

Features	Dumpsites	Sanitary landfills
Design	Unregulated and open	Engineered, safe, and closed
Environmental impact	High potential risk for pollution	With leachate treatment and gas management
Prevalence in India	Bagun Hathu (Jamshedpur)	Narela-Bawana (Delhi)

Abbreviation: HH: Households.

Figure 5. Composting plant at Bara Dih (windrow composting)

(iii) A sanitary landfill is a highly sophisticated disposal mechanism incorporating leachate removal, treatment, and methane gas collection facilities. TSUISL is currently constructing a sanitary landfill.

4.3. Environmental impacts

Open dumps near rivers have a severe impact on water bodies and ecosystems since toxic leachate from decomposing waste pollutes groundwater and harms aquatic life.[36] TSUISL's composting program helps to divert organic waste from landfills. The aerobic decomposition process directly helps to cope with climate change by reducing methane emissions, a type of greenhouse gas that is 25 times more potent than carbon dioxide.[37] Beyond this, yard waste and food scraps break down into nutrient-rich composting, improving the condition of rebooting soil and lowering reliance on synthetic fertilizers. This strategy protects groundwater and rivers from pollution and offers a platform to address urban waste issues.

5. Recommendation plans for effective integrated solid waste management (ISWM)

TSUISL demonstrates its success in effectively managing Jamshedpur's municipal services through the strategies and plans implemented in the solid waste management system. However, specific gaps impede its full potential effectiveness. The study identified several gaps, leading to developing suggestions to improve the current MSW management.[38]

(i) Collection: It is recommended to relocate community bins near residential blocks and commercial areas. Using closed containers instead of open bins and masonry bins is recommended. Enforcement of door-to-door collection with the separate-bin concept in residential and market areas is required[39]

(ii) Segregation: Providing two bins ensures that waste separated at its source can be collected efficiently. It is strongly advised not to collect mixed waste during door-to-door collection by workers. Separating biodegradable waste at its source allows for convenient processing at a compost plant. This approach saves time, reduces the need for additional workers, and produces high-quality compost free from contaminants. Workers receive clear instructions to wear safety gear while handling MSW to prevent injuries or infections[31]

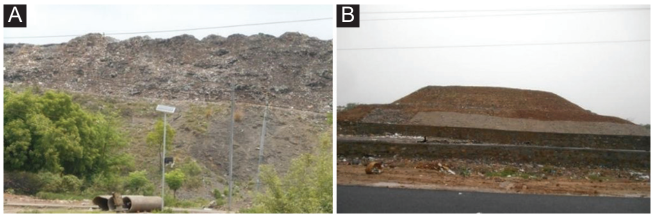

Figure 6. Disposal sites of Jamshedpur city. (A) Open dumping site at Baugun Hathu. (B) Semi-scientific landfill near XLRI, Marine Drive.

(iii) Transportation: We recommend using a neural network system for route-optimizing techniques and planning collection routes. A neural network approach will ensure maximum collection efficiency while optimizing transportation costs[40]

(iv) Treatment: The MSW of Jamshedpur contains a significant amount of biodegradable components, making composting and bio-methanation treatment effective for managing the wet organic fraction. Meanwhile, managing the combustible fraction of MSW can be achieved using refuse-derived fuel (RDF). The MSW management rule (2016) approved by the government has already mandated a threshold for fuel consumption such as RDF at 5% by industries[41]

(v) Landfill: In Jamshedpur, it is advisable to choose a sanitary landfill instead of an open dumpsite or semi-operated landfill due to two dumpsites near the Subarnarekha River in the study area (Figure 6). There is a potential risk of leachate percolation and contamination of river water.[36]

6. Conclusion

In developing nations, managing solid waste is a significant challenge. This study intended to assess the effectiveness of the ISWM plan, which aims to alleviate the strain on landfills and promote waste segregation, focusing on recycling and reuse. In addition to recycling metals, TSUISL constructs roads using plastics. It also recognizes the environmental issues caused by the plastics manufacturing and recycling industries. TSUISL also runs a large-scale composting plant to efficiently handle biodegradable waste, with biomethanation processing at 40 tonnes/day. By estimation, we found that the collection charge per ton of waste is ₹150 ($1.80) as per available resources.

The study highlights how a public–private partnership effectively addresses financial and technical constraints. This approach may resolve the problem of inadequate finance for waste management in urban local bodies. Cooperation between the government and private sector can significantly enhance India's MSW management services.

Acknowledgments

The authors acknowledge the support from the participants of this research.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data will be available from the corresponding author upon reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 33-41.
doi: 10.36922/ajwep.8113

ORIGINAL RESEARCH ARTICLE

Weathering of volcanic eruption products and rivers contamination in Kamchatka

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Received: December 21, 2024; 1st revised: February 7, 2025; 2nd revised: February 11, 2025; 3rd revised: February 21, 2025; Accepted: February 24, 2025; Published Online: March 5, 2025

Abstract: We investigated the biochemical weathering of unaltered lava and scoria samples from Tolbachik volcanic field (Kamchatka). An experimental study on leaching of main (Si, Fe, Mg, Al, and Ca) and trace element constituents (Li, Sr, Ba, V, Mn, Co, Ni, Cu, Ti, and other trace metals) was conducted. We used a 0.01 M (pH 2) solutions of oxalic and acetic acids as analogs of natural bioorganic solvents. Meanwhile, a constant mass ratio of solid and liquid phases was maintained. The results suggested that the mobilization of trace elements occurs mainly as a result of the destruction of the crystalline structures of rock-forming minerals. In the case of oxalic acid solution, Fe(III) and Mn(IV) oxyhydroxides are reduced to soluble Fe(II) and Mn(II) compounds. The formation of organic complexes increases the stability of metals in solution and makes it possible to achieve significantly higher concentrations of dissolved forms than in the absence of organic ligands. For example, water that has passed through an old lava field covered with lichen may contain 2.5 times more Co than the maximum permissible concentration for fish reproduction. This study demonstrated that the spikes in concentrations of heavy metals in the Kamchatka River, observed during the 2015 – 2016 period, can be explained by the leaching of fresh products from the Tolbachik Fissure Eruption (2012 – 2013).

Keywords: Leaching; Mobilization; Organic acids; Volcanic rocks; Heavy metals; Weathering

1. Introduction

The uniqueness of the Kamchatka Peninsula (Russia) lies in the fact that its territory contains the largest areas of natural spawning grounds of Pacific salmon in Asia (Figure 1). As world experience has shown, any economic development of the territory negatively affects the reproduction of salmon. The strategy of integrated development of the territory, which was adopted in Kamchatka, includes the development of mineral deposits, in particular gold, polymetallic ores, and platinum. The primary source of the overwhelming majority of valuable metals is magmatic rocks. Their weathering leads to the selective transition of chemical elements into a dissolved state. The development of the mining industry inevitably leads to the degradation of spawning rivers and a decrease in their fisheries potential.[1]

In recent years, when studying the formation of industrial ores, much attention has been paid to trace elements responsible for modern technological development. An important role in the weathering

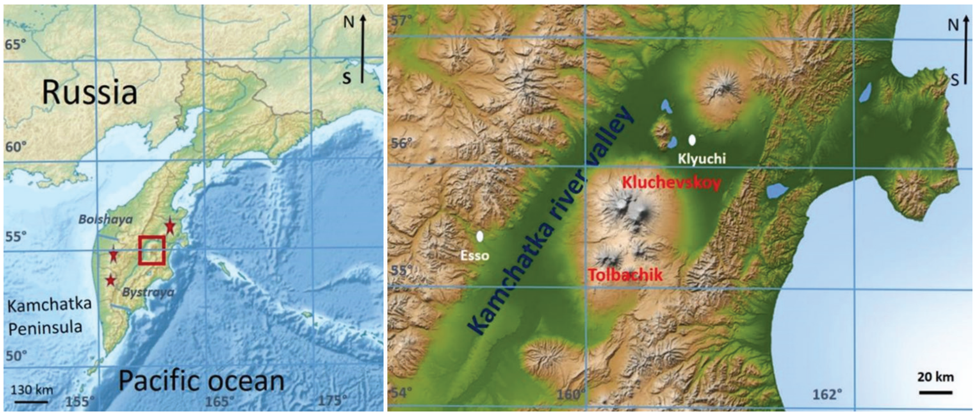

Figure 1. Geographical location of Kamchatka Peninsula (left); Klyuchevskoy and Tolbachik volcanoes (right). Adopted from https://en.wikipedia.org/wiki/Kamchatka_Peninsula

process constitutes organic acids, which not only create an aggressive acidic environment but also form strong complex compounds stable in aqueous solutions. To date, extensive experimental and numerical studies have been conducted on the mobilization of the main petrogenetic elements (Si, Al, Fe, Mg, Ca, Na, and K) on the interaction of ash, rocks, and rock-forming minerals with natural organic acids solutions.[2-4] However, there are very little relevant data on important trace metals, as some of them are toxic. Subduction zones with active volcanism represent promising search areas where large reserves of some metals have already been discovered.

2. Kamchatka' regional rivers

A large amount of precipitation (up to 2,700 mm per year), the presence of permafrost, long-melting snow in the mountains, low evaporation, and mountainous terrain[5] are the reasons for the development of an exceptionally dense rivers network within the Kamchatka peninsula (Figure 1). There are about 140 thousand rivers and streams in Kamchatka, but only 105 of them are over 100 km long. Despite the shallow depth, the rivers possess exceptionally high water flux. The main Kamchatka river (758 km long) and the Penzhina river (713 km) stand out sharply in size. Most Kamchatka' rivers flow in a latitudinal direction, which is elongated in the north-south direction of the main watersheds: the Middle and Eastern ridges. Both of them are chains of extinct and active volcanoes, where the Klyuchevskoy volcano group (55°90' north latitude, 160°60' east longitude) is the largest active center in Asia.[6]

Fishing and the fish processing industry are the main sectors of the Kamchatka' economy with 20% of regional gross product. Kamchatka is the leader in extraction of aquatic biological resources among the regions of not only the Far East (about 45%), but also Russia as a whole (above 30%).[7] Salmon fishing provides 30 – 40% of the income of the fishing industry in the region. Mining (platinum, placer and indigenous gold, associated silver, polymetallic ores, gas and coal for local needs, and drinking and mineral water) is growing on the territory of the Kamchatka, providing 5.6% of regional gross product. Nevertheless, the territory of the Kamchatka remains one of the most ecologically prosperous. The region has the largest areas of natural spawning grounds for Pacific salmon in Eurasia. Despite the low level of urbanization, the Kamchatka region is no exception and is subject to anthropogenic impact. Kamchatka has adopted a strategy for the integrated development of the territory, including the development of minerals, in particular deposits of polymetallic ores. The current gold, copper, and nickel deposits under development are marked with asterisks on Figure 1 (left).

We have studied the data on the main heavy metals of the rivers to separate natural and technical sources. To assess the degree of contamination, we relied on state sanitary standards governing the maximum permissible concentrations (MPC) of metals and other inorganic compounds in drinking water.[8]

2.1. Copper (MPC_{Cu} = 1 mg/L)

In the Kamchatka Peninsula, there are complex manifestations of copper-copper ore, copper-molybdenum, and copper-polymetallic ore manifestations. The soils of Kamchatka are characterized by a high content of copper. Copper, to a greater extent, together with iron hydroxide, is carried into reservoirs with soil solution. As a result, copper contamination is characteristic of all spawning rivers of the region, with a repeatability of values above the threshold of 57 – 100%, in which the copper content exceeded the MPC by 1.5 – 6 times.

One-time elevated concentrations (1.1 – 7.6 MPC) were detected in all watercourses in various hydrological seasons. Meanwhile, copper compounds are a characteristic impurity for 55% of watercourses. The highest concentration of copper is typical for the Ozernaya river due to the release of thermal waters and leaching of copper from bedrock, as well as for the Kamchatka river and the 1-Mutnaya river due to leaching of copper from bedrock. Concentrations exceeding 10 MPC are typical for high water, low water, and rain flooding. Thus, the maximum excess of MPC was registered in 2015 – 2016 in the Kamchatka river.[9] It is worth noting that this high level of 1-time indicator of copper contamination coincided with a large fissure eruption of Tolbachik volcano (see description below).

2.2. Iron (MPC_{Fe} = 0.3 mg/L), zinc (MPC_{Zn} = 1 mg/L)

For more than half of the studied rivers, an increased contents of total iron and zinc were noted. The average annual value of total iron in the Uksichan river (a second-order inflow of the Kamchatka river), the Bolshaya river and the Bystraya river increased by 2 times; in the rest, it has changed little (Figure 1, left). A significant excess (11.4 MPC) was recorded in the Krasnaya river (an inflow of the Avacha river) during the flood recession. The maximum excess of the total iron content was observed in 2014 during high water on the closing section near the village of Klyuchi (18.2 MPC), near Klyuchevskoy volcano group (Figure 1, right). Zinc, as a contaminant, is typical for all the studied rivers, but its average annual concentration did not exceed 2.3 MPC. In 2015, the content of zinc compounds increased by an average of 8.5 times, and zinc became an impurity for 80% of the surveyed water bodies. The highest zinc content was noted at the peak of high water on the Bystraya river below the Esso village (6.8 MPC).

2.3. Lead (MPC_{Pb} = 0.01 mg/L), cadmium (MPC_{Cd} = 0.001 mg/L)

Lead is a characteristic contaminant for the basins of the Bolshaya, Bystraya rivers, most of the Avacha River' basin, especially the Srednyaya Avacha River, as well as the basins of the Bolshaya Vorovskaya, Bystraya rivers (inflow of the Paratunka river) and inflows of the Kamchatka river (Bersh, Kavycha, Uksichan). On the Kamchatka river section near the village of Dolinovka in 2015 and in 2017, the highest single content of lead compounds in the Bersh river during a high water was found as 2.5 MPC.

At low water period, maximum concentrations of cadmium were found in the water of the Udova and Bolshaya Vorovskaya rivers as 2.9 and 2.99 MPC, respectively. Isolated manifestations of cadmium contamination have been recorded for the Kamchatka rivers (Kozyrevsk and below Klyuchi), Kirganik and Avacha.

3. Contribution of active volcanoes' eruption

Tolbachik volcanic fissure zone is located in the southern part of the Klyuchevskaya group of volcanoes (Figure 1, right). It is the northern end of the Kuril–Kamchatka volcanic belt, near the intersection of the Kuril–Kamchatka and Aleutian Island arcs. Tolbachik comprises the three main parts: two cones, Ostry Tolbachik, the Plosky Tolbachik and Tolbachinsky Dol. The last one is the lava-pyroclastic plain adjacent to the southern slopes of Plosky Tolbachik (Figure 2 and Supplementary File Figures 1-4). Ostry and Plosky Tolbachik began to form about 7 – 10 thousand years ago.[10] The first large scoria cones were formed 2000 – 1500 years ago and mainly consisted of magnesian basalts. The paleofumarolic fields of scoria cones are rich in Zn, Cu, and Pb mineralization, including their minerals as tenorite, anglesite, atacamite, antlerite, pyromorphite, *etc.*[11]

The largest eruptions with the formation of scoria cones in recent years took place in 1975 – 1976 (the Great Tolbachik Fissure Eruption, GTFE) and 2012 – 2013 (Tolbachik Fissure Eruption [TFE],

Figure 2. Kamchatka's volcanoes as part of the Pacific Ring of Fire, and the view of the Tolbachinsky Dol (55°20' north latitude, 160°20' east longitude)

see Supplementary File Figures 1-4). They were predominantly basaltic, with two distinguished types: high-magnesian and high-alumina basalts. During the early eruption of 1975 (Northern Breakthrough, scoria cones I, II, and III), pyroclastic ejections predominated in composition corresponding to magnesian basalts. Their main minerals are olivine (Fo85 – 99), diopside, diopside-augite (Ca42 – 45-Mg 44 – 50-Fe 7 – 11), and plagioclase (An74 – An55). The main stage of the 2012 – 2013 eruption (*e.g.*, scoria cone Naboko) was characterized mainly by basaltic lavas. Compositionally, plagioclase of Naboko vent lavas ranges from An70 – 72 to An80 – 80, olivine ranges from Fo64 to Fo75 (mainly found as microphenocrysts), and clinopyroxene ranges from augite to salite.[12] Fumarole activity of GTFE and TFE continues until the present day.[13] The fumaroles of the scoria cones are characterized by a wide variety of minerals and mineral-forming elements. A significant number of new minerals were discovered there.[14]

We know of only a few works that studied the effect of organic acids on the transition of trace metals from rocks to a dissolved state. From a methodological point of view, these studies were imperfect – first, they lacked either the initial content of trace metals in rocks[15]; second, the magnitude of mobilization was determined depending on the specific composition of the magmatic rock.[16] The purpose of our work was to determine the quantitative characteristics of the trace metals' mobilization from magmatic rocks under the action of dilute solutions of organic acids, which are typical components of surface and groundwater in volcanic regions. Many of the above metals are toxic and their high presence in natural waters is dangerous for agriculture and people.

4. Extraction method

To study the weathering features of volcanic rocks (laboratory simulation of biochemical weathering processes), we used unaltered fresh lava and scoria (fractions from 0.1 mm to 2 cm) from the Tolbachik volcano, Kamchatka. Samples were collected during the expedition of our team from the Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences (GEOKHI RAS) in 2020 to the Kamchatka Peninsula. The scoria samples were treated with distilled water and 0.01 M of oxalic (HOOC-COOH) and acetic (CH_3-COOH) acids. The acid solutions were prepared by thorough mechanical mixing with distilled water – first, from a solid powder of oxalic acid (99.75% purity); second, with the acetic acid precursor (100% purity), in accordance with Russian state standard #19814 – 74. The chemical composition of volcanic scoria is given in Tables 1 and 2. The experiments were carried out for water and acid with a mass ratio of rock and solution equal to 1:10 (50 g sample and 500 mL solution). In some cases, suspensions were stirred daily in an ultrasonic bath for a consecutive 5 days, with 15 min each time, and then the solutions obtained after leaching (extract) were decanted.

The microelements content in the extract was determined by our team with inductively coupled plasma atomic emission spectroscopy (ICP-AES) method iCAP6500 (Thermo Scientific). ICP-AES is heavily used at GEOKHI RAS. It allows for determination of the multi-element composition of the studied objects. The principle of the method is that the test sample is transferred to a solution, which is sprayed into the device in the form of an aerosol. The study was carried

Table 1. Main elements composition of various Tolbachik lava and scoria samples[a]

Main oxide, wt. %	Scoria, s1	Scoria, s2	Lava, l1	Lava, l2
SiO_2	50.57	55.69	51.06	55.98
Na_2O	2.95	3.12	3.37	3.41
MgO	6.43	5.11	4.15	3.14
Al_2O_3	13.54	14.59	12.68	13.60
K_2O	1.26	1.87	2.37	3.45
CaO	10.42	8.71	8.84	6.29
FeO_{tot}	12.59	8.41	13.84	10.15

Note: [a]Our team carried out analysis using X-ray fluorescence (XRF) method in GEOKHI RAS.
Abbreviation: GEOKHI RAS: Geochemistry and analytical chemistry of the Russian academy of sciences.

Table 2. Trace metals abundance of the Tolbachik scoria samples (μg/g)

Element	Concentration	Element	Concentration
Li	20	Nb	7
Cs	2.2	Mo	7
Ba	582	Ag	0,1
V	276	Sn	1,6
Cr	4	Sb	0,46
Co	22	Te	<0.05
Ni	9	Rb	64
Cu	242	Sr	329
Zn	103	Y	40
Ga	19	Zr	237

out at atmospheric pressure by use of inert gas (most often, argon). The ICP-AES method is widely utilized in geology because it allows simultaneous determination of a large number of macro- and micro-components. Meanwhile, elements could be in a dissolved sample within wide detection limits (from tenths of ppm to tens of thousands of ppm).

At a constant initial content of organic acid in the solution, the concentration dependence C_i, of the leached microelement i (μg/L) on the mass ratio of rock to solution (m, g/L), satisfy the following conditions: $C_i \rightarrow 0$ at $m \rightarrow 0$ (leaching does not occur) and $C_i \rightarrow$ Const at $m \rightarrow \infty$ (all dissolved acid has reacted). These conditions correspond to the simplest hyperbolic function:

$$C_i = k_i \cdot x_i \cdot m/[1+ x_i \cdot m] \quad \text{(I)}$$

where x_i is the content of element i in the volcanic rock (μg/g); k_i = const is extraction factor or leaching coefficient (LC). For low values of the mass ratio of rock to solution, that is, for $x_i m << 1$, Equation I takes the simpler form:

$$C_i \approx k_i \cdot x_i \cdot m. \quad \text{(II)}$$

The initial masses of the samples were the same, allowing us to calculate the values of the relative LC of microelements k_i as the ratio C_i/C^*_i, where C^*_i is the microelement concentration after distilled water extraction without ultrasound shaking.

According to Table 3, shaking allows to identify elements carried by a suspension (Al, Cu and Fe), but does not crucially affect their extraction with water. Evidently, elements such as Al, Ba, Ca, Cu, Co, Cr, Fe, K, Li, Mg, Mn, Ni, P, Si, Sr, Ti, and V were extracted by oxalatic acid much better than by pure water, that is, LC (ox) >10. Elements such as Ba, Ca, Na, K, Li, Mg, and Sr are members of alkali and alkaline earth elements group and also the components of the aluminosilicate

Table 3. Concentration of elements (mg/L) after leaching of Tolbachik volcano's scoria[a]

Element	After shaking H_2O, C	Without shaking H_2O, C^*_i	Oxalatic acid, C_i^{Ox}	LC (ox), C_i^{Ox}/C^*_i	Acetic acid, C_i^{Ac}	LC (ac), C_{iAc}/C^*_i
Al	0.45	0.06	31.6	526.7	5.4	90
Ba	0.01	0.01	0.21	21	0.06	6
Ca	2.17	1.72	18.8	10.93	11.0	6.4
Cd	<0.001	<0.001	0.004	>4	0.004	>4
Co	<0.001	<0.001	0.025	>25	0.002	>2
Cr	0.002	<0.001	0.010	>10	0.004	> 4
Cu	0.07	0.02	2.66	133	1.15	57.5
Fe	0.69	0.21	63.9	304.3	1.31	6.23
K	0.45	0.48	7.09	14.77	1.51	3.15
Li	0.004	0.004	0.04	10	0.01	2.5
Mg	0.60	0.54	18.93	35	1.91	3.54
Mn	0.02	0.01	1.15	115	0.17	17
Mo	<0.001	<0.001	0.004	>4	<0.001	<1
Na	5.16	5.78	20.4	3.53	7	1.21
Ni	0.002	0.003	0.03	10	0.01	3.33
P	0.08	0.03	1.35	45	0.04	1.33
Pb	0.13	0.02	0.04	2	0.29	14.5
S	0.82	0.90	1.71	1.9	0.43	0.47
Si	3.23	2.56	45.7	17.85	8.44	3.29
Sr	0.009	0.006	0.18	30	0.06	10
Ti	0.08	0.02	1.26	63	0.08	4
V	0.005	0.003	0.31	103.3	0.002	0.7
Zn	0.09	0.08	0.19	2.37	1.01	12.6

Note: [a]Two independent extractions from scoria were performed: one – with diluted oxalic acid (pH 2); other - with diluted acetic acid (pH 2).

minerals. Apparently, their extraction is associated with the dissolution of the rock. Furthermore, elements with variable valence such as Co, Fe, Mn, and Ni could be reduced in the presence of oxalic acid to highly soluble compounds. Elements such as Al, Cu, Mn, Pb, Sr, and Zn were extracted by acetic acid much better than by pure water, that is, LC (ac) >10.

5. Results and discussion

Liquid differentiation occurs in basaltic melts due to the contrasting roles of two types of structural components – first, network-formers; second, network modifiers. According to the modern state of science, the basic structural unit – SiO_4 tetrahedron – can form one-, two-, or three-dimensional networks and clusters. If the network is completely polymerized, then each Si–O–Si bridging oxygen is shared by two SiO_4 tetrahedra. Usually, network-forming cations (in silicate melts primarily Si^{4+}, including Al^{3+}, Fe^{3+}, and Ti^{4+}) are surrounded by oxygen ions in bridging position (Si–O–Si). However, network-modifying cations are surrounded by oxygen ions in non-bridging positions (Si–O–M), where M denotes the six-fold coordinated by oxygen network-modifying cations (as a rule, Mg, Fe[II], Ni, *etc.*). During melt separation, the chemical elements are distributed among the two conjugates according to melt structure, which depends on composition, the number of volatiles, pressure, and temperature. Finally, the solubility of an igneous rock will be determined by the stability of its constituent minerals.

According to energy-dispersive X-ray analysis, main rock-forming minerals of Tolbachik volcanic rock are Ca-rich plagioclase, Ca-Mg-rich pyroxene (diopside), Mg-rich olivine, and K-feldspar. Amount of minerals varies from sample to sample. Secondary minerals are Mg-rich mica phlogopite ($KMg_3(AlSi_3O_{10})(OH)$) and alunite ($KAl_3(SO_4)_2(OH)_6$). Moreover, a number of Cu, Zn, and Pb fumarolic minerals were found: tenorite (CuO), chalcanthite ($Cu(SO_4)\cdot 5H_2O$), atacamite ($Cu_2Cl(OH)_3$), pyromorphite ($Pb_5(PO_4)_3Cl$), linarite ($CuPb(SO_4)(OH)_2$), anglesite ($Pb(SO_4)$), and diopside with Cu, Zn-impurities ($CaMgSi_2O_6$).[13]

In general, basaltic lavas are prone to rapid crystallization in an open system due to degassing and cooling.[17] For example, a general sequence of the Tolbachik fissure zone comprises the two extreme types of basalts, which differ primarily in the content of Mg and Al: Middle-K, high-Mg (Mg/Al: 2.1) basalts, and high-K, high-Al (Mg/Al: 0.45) basalts.[12] Typical chemical composition of fresh scoria and lava samples collected by our team on Tolbachik lava field (TFE 2012 – 2013) is presented in Table 1. Similar analytical results were reported in the form of BSE images and tables with the energy dispersive spectroscopy point analysis in a published paper.[18]

Compared to lava, scoria is enriched with refractory metals (such as Ca and Mg), but it is depleted with volatile elements (such as Na and K). Our team analyzed trace metals abundance of the above samples using AES with ICP-AES method in GEOKHI RAS on iCAP6500 (Thermo Scientific) and the results are presented in Table 2. The procedure for preparing samples was described in detail in a TFE study.[19]

In natural environment, many weeds (such as nettles) secrete acetic acid, whereas lichens secrete oxalic acid, mainly. Meanwhile, lichens are the most primitive species and are the first to populate fresh lava fields. Having compared the values of the LC(ox)/LC(ac) in Table 3, we inferred that oxalic acid efficiently extracts some elements much better than acetic acid. Hence, the appearance of lichens significantly accelerates the process of biochemical weathering of magmatic eruption products. We grouped the elements according to the power of extraction by different organic acids, as shown in Table 4.

The mechanism of chemical weathering mainly concentrates elements of the first group. For alkaline elements, nickel, chromium, and other metals that are part of the silicate matrix of the rock, mobilization is associated with its destruction. It is known that water is an excellent solvent for rocks and minerals. The main chemical reaction of water with minerals of igneous rocks (hydrolysis) leads to the replacement of alkaline elements' cations of crystal lattice with hydrogen ions of dissociated water molecules, like

$$KAlSi_3O_8 + H_2O \rightarrow HAlSi_3O_8 + KOH \quad \text{(III)}$$

The resulting bases (NaOH, KOH, and others) compose an alkaline medium of the solution, in which further destruction of the plagioclase crystal lattice occurs also, the interaction of water with rock minerals leads to hydration, that is, the attachment of water particles to mineral particles, like

$$2Fe_2O_3 + 3H_2O \rightarrow 2Fe_2O_3\cdot 3H_2O \quad \text{(IV)}$$

The second group, including vanadium, manganese, iron, cobalt, and titanium, is characterized by an order of magnitude higher extraction values in oxalic acid solution compared with solutions of other acid. Taking into account the reducing properties of oxalic

Table 4. Differences in leaching factors for elements from Tolbachik scoria

Element	LC (ox)/LC (ac)
Group 1	
Ca	1 0.71
Mo	≈ 4
Cr	2.62
Cu	2.31
Na	2.92
Ni	3.69
Sr	3.13
Li	3.70
K	4.69
Ba	3.47
Al	5.87
Si	5.42
Group 2	
Co	10.96
Fe	48.77
Mg	9.90
Mn	6.66
Ti	16.74
V	128.92
Group 3	
Cd	≈ 1
Zr	≈ 1
B	≈ 1
Group 4	
Pb	0.15
Zn	0.18

acid, we infer that micro-grains of Fe(III) and Mn(IV) oxyhydroxides, which may be present in the samples, are reduced in its presence to divalent iron and manganese compounds that are highly soluble in an acidic medium. Since vanadium, cobalt, and titanium are well adsorbed by Fe(III) and Mn(IV) oxyhydroxides, we infer that the reduction of the latter will be accompanied by a transition to the dissolved state of the adsorbed metals, as observed in our experiments.

The third group, including cadmium, zirconium, and boron, is characterized by weak and approximately identical extraction values. The reason that the elements of this group do not have noticeable differences in the mobilization by different acids is not clear. The processes of complexation in this case should not play a big role, inasmuch as organic acids were used in the experiments, which differ greatly in their complexing ability. Perhaps the bulk of the elements of the third group is present in the scoria as microscopic grains of mineral phases that are poorly soluble in a slightly acidic medium. The fourth group includes lead and zinc, specifically. Their LC(ac) is several times higher than LC(ox), that is, extraction with acetic acid is more effective. This may be attributed to the good solubility of lead and zinc acetates.

6. Conclusion

The present study has shown that biochemical weathering for some important metals is significantly more effective in the presence of oxalic acid. Earlier biochemical expeditions have shown that oxalic acid salts (oxalates) are present under lichens on the slag cones of the Tolbachik volcano.[20] New lichen species have been discovered that are capable of producing oxalates in large quantities in the soil. Acetic acid is released by more evolved higher plants – grass and bush. Due to the organic ligands, the leaching factors of the main water contaminants increase very significantly (relative pure water leaching): Cu – 133 (57), Fe – 304 (6), Al – 526 (90), Mn – 115 (17), Pb – 2 (14), and Zn – 2 (12), for oxalic (acetic) acid salts.

Based on the analysis of crystal morphology, it was concluded that the growth of crystals alternates with their dissolution in the process of biomineralization. Lichens are widespread on the Kamchatka Peninsula and are among the first living organisms to grow on volcanic formations.[21] The predominant group is crustose lichens, which are well known for colonizing stony substrates of various chemical compositions.[22] Due to their active metabolism, lichens interact with bedrock minerals, which leads to extensive oxalate formation.[23] On the basis of obtained results, we attributed the spikes of heavy metal concentrations in the Kamchatka river during the 2015 – 2016 period to the leaching of fresh Tolbachik' (TFE 2012 – 2013) eruption products.

From Group 2, cobalt (Co) and its compounds are most toxic for human when ingested in high doses. Its inorganic compounds are known to have carcinogenic and mutagenic effects, too. For example, sulfate $CoSO_4$ and octacarbonyl cobalt vapors $Co_2(CO)_8$ are especially toxic. The toxic lethal dose (LD50 for rats) is 50 mg. The MPC of cobalt dust in the air is 0.5 mg/m^3, whereas in drinking water, the MPC of cobalt salts is 0.1 mg/L. Meanwhile, the quality of water for the protection of aquatic life is subject to stricter requirements: MPC_{Co}

is 0.01 mg/L for fish. Thus, the water that has passed through the old lava field covered with lichen may contain 2.5 times more cobalt than its MPC for fish reproduction.

Unexpectedly, vanadium was particularly sensitive to the presence of oxalic acid in water solution. It is known that the main reserves of industrial vanadium-containing ores are concentrated in magmatic deposits. According to some estimations, they account for about 95.4% of all reserves of these ores, and only 4.6% of the reserves are exogenous deposits. At present, about half of the vanadium, produced globally, is obtained from ores of endogenous deposits (35 – 40% is accounted for by Bushveld). The formation of the weathering crust of these rocks with the participation of organic acids may be an important concentration factor in the presence of proper geochemical barriers.

Acknowledgments

The work was carried out according to the state assignment of GEOKHI RAS.

Funding

None.

Conflict of interest

The authors declare that they have no conflicts of interest.

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Availability of data

Data are available from the corresponding author on reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 42-51.
doi: 10.36922/ajwep.8434

ORIGINAL RESEARCH ARTICLE

Bioremediation of heavily polluted Bagmati River water in Kathmandu Valley, Nepal, using *Moringa oleifera* seed extract

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Received: January 7, 2025; 1st revised: February 14, 2025; 2nd revised: February 19, 2025; Accepted: February 19, 2025; Published Online: March 6, 2025

Abstract: The precious Bagmati River water is deteriorating continuously due to the loading of effluents from different sources. The water quality of the Bagmati River water was determined by collecting water samples from Pashupati (B-1) and Balkhu (B-2) sites of the Bagmati River in Kathmandu Valley. The observed water quality parameters indicated that the Bagmati River is extremely polluted, and pollution was more pronounced downstream after the confluence of its tributaries. The total coliform count was extremely high, and bacteria levels exceeded the limit of counting, indicating fecal pollution from domestic influents. After treatment with indigenous *Moringa oleifera* (MO) seed extract, the black-colored water became clear. Most probable number and spread plate count of coliform progressively decreased with increasing concentrations of MO seed extract. The hardness, turbidity, iron, and chromium concentrations were reduced to below the World Health Organization standard after treatment with 100 mg/L MO and citric acid-treated seed extracts. The results suggest that the treated and untreated MO seed extracts could be a good natural coagulant for polluted river water treatment to reduce physicochemical and microbial pollutants.

Keywords: Coagulant; Chromium; Iron; Moringa oleifera; Water pollution

1. Introduction

Clean and safe water plays a dynamic role in human life. The use of surface water for drinking and domestic purposes is a common practice in communities of developing countries like Nepal. The rapid population growth, industry, and the excessive use of chemical fertilizers are increasingly polluting surface water. Therefore, obtaining safe drinking water is one of the biggest problems for people, especially those living in developing countries.[1] People from poor communities are using polluted river water without any purification or pre-treatment, leading to waterborne diseases, such as dysentery, diarrhea, cholera, and skin disease.[2,3] The Bagmati River is precious and important in the geography, culture, hydrology, and socioeconomic development of Nepal. Recently, the effluents from various sources degraded the Bagmati River water, mainly in Kathmandu Valley, increasing the levels of harmful chemicals and undesirable biological contaminants.[4] Thus, the treatment and purification of surface water using effective and inexpensive techniques is essential for safe domestic use and for preventing casualties from waterborne diseases. Among the techniques used for water disinfection, chlorination is the most effective and cheap technique. However, residual chlorine can react with different organic substances, converting them into carcinogens, such as trihalomethane.[5] Another chemical coagulant, aluminum sulfate (alum), is also used for water purification; however, residual alum is potentially hazardous to human health, and relatively high concentrations are linked to Alzheimer's disease.[6] Hence, locally available natural coagulants, such as *Moringa oleifera* (MO), offer a non-toxic alternative for treating turbid and polluted water.[7-9]

MO belongs to a cultivated species of the *Moringaceae* family.[10] It was introduced to Africa from India for use as health supplements.[11] It is a fast-growing, medium, or small tree found in the tropical and subtropical regions of northern India, as well as different parts of Asia, Africa, and South America.[10,11] Different parts of MO are useful for bio-remediation and water purification.[12-15] MO seeds contain a protein suitable for binding to toxic materials.[16,17] The positively charged surface molecules attract negatively charged particles from water through adsorption and form a larger molecule (floc), which is capable of removing heavy metals and dirt, as well as killing bacteria from contaminated waters.[18,19] Omodamiro *et al*.[20] evaluated the activity of ethanolic extract MO seeds in water purification and revealed that the seeds possess inhibitory potential against various pathogens, improving the physicochemical properties of the water sample. The present study explored the effect of different concentrations of MO seed extract for the treatment of heavily polluted river water and compared the results with that of citric acid-modified MO seed extract (CAMO).

2. Materials and methods

Dried MO seeds were collected from a local market in Kathmandu, Nepal. The seeds were shielded and dried for 3 days at 30°C. The seeds were ground to a fine powder and sieved using a 212 µm sieve aperture. The surface functional group content of the MO and CCMO seed powder was determined using Fourier transform infrared spectroscopy (FTIR; Nicolet 4700; Thermo Eectron, USA). CAMO was prepared by stirring a mixture of MO seed powder and 0.1 M NaOH at 300 rpm for 1 h. The excess base was removed by washing the mixture with double-distilled water and then mixed with citric acid in a 1:7 mass by volume (g/mL) ratio. The slurry was kept at 50°C overnight, subsequently washed with distilled water, and the excess citric acid removed. The treated seed powder was dried and sieved to retain fine powder. The citric acid-modified seed powder was stored in a plastic bottle in a refrigerator, for use in water treatment. The required amount of powder was dissolved in 100 mL distilled water stirred for 1 h with a magnetic stirrer and filtered using Whatman 41 filter paper used as stock solution. Fresh solutions of MO and CAMO were prepared daily to avoid aging effects. The calculated volume of stock solution was added to the water sample to obtain 50, 100, and 200 mg/L concentrations for the treatment. The mixture was shaken at 200 rpm for 10 min to ensure total dispersal of coagulant and at 30 rpm for 30 min to aid effective flocculation of colloidal particles, then left for 1 h for the flocs to settle. The supernatant (water) was collected and analyzed for various parameters.[21-23]

Sample water was collected from two different sites of the Bagmati River; one was the Pashupati area (B-1) before the confluence of its tributaries, and the other was the Balkhu area (B-2) after the mixing of tributaries to the mainstream Bagmati River in Kathmandu valley (Figure 1). The samples were collected in sterilized biological oxygen demand (BOD) bottles (3), Q transported to the laboratory using a cooler box and stored in a refrigerator for subsequent physicochemical analysis and treatment. For microbiological analysis, the samples collected in the sterilized BOD bottles were kept in a zip-lock pouch and then transported into the laboratory using a cooler box for immediate analysis. Water quality parameters were measured according to the standard procedure; pH was measured using a digital pH meter (CE, pH600AQ; Milwaukee, USA), turbidity was measured using a digital nephelometer (no. Digital Turbidity Meter 341; Electronics India, India), and conductivity was measured using a conductometer (CE, 1739; NSAW, India). Total hardness was determined by complexometric titration, and the concentration of heavy metals (Cr and Fe) was determined using a visible spectrophotometer (ELICO, SL-177; Hyderabad, India).[22,23] Before the determination of iron concentration, ferric ions were reduced to ferrous ions by boiling with hydroxylamine hydrochloride, while chromium was oxidized into hexavalent chromium using potassium permanganate. The total iron was determined using phenanthroline, and chromium was determined using diphenylcarbzide methods. Bacteriological parameters were estimated using the most probable number (MPN) method and the spread plate count (SPC) method. The MPN technique was conducted in three steps: presumptive, confirmed, and completed tests. In the presumptive test, known amounts of samples were tested in 10 sterile Durham tubes. The inoculated broths were then incubated at 37°C for 24 h. The change in color and gas formation

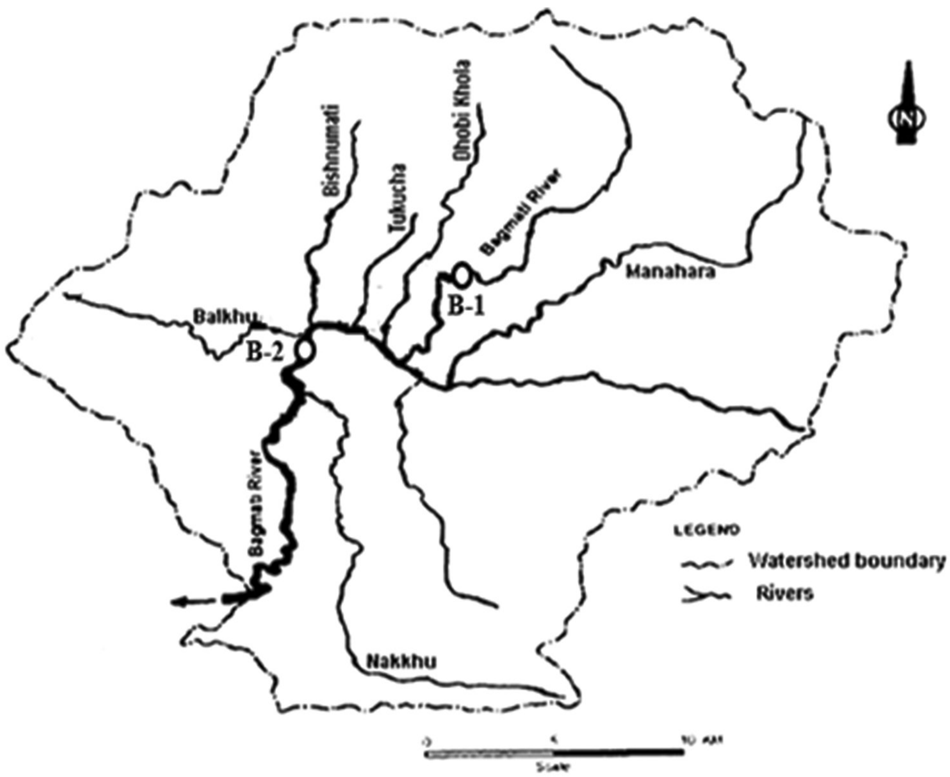

Figure 1. Map of the Bagmati River and sampling sites

were considered presumptive positive for coliform bacteria. The MacConkey agar medium was used for the confirmed test. Water samples from the positive confirmed test were incubated on nutrient agar and lactose broth at 37°C for 24 h. The quantitative analysis was acquired using the membrane filter method, in which 100 mL of the samples were placed on the MacConkey agar media by passing through 0.45 µm filter paper. The samples were then incubated for 24 h, and bacteria were counted after incubation.[24] The isolation and counting of the viable microorganisms in the water sample were determined using the SPC technique. Briefly, 9 mL of sterile distilled water was added to separate test tubes and 1 mL of sample water was added to the first test tube; from the first test tube, 1 mL of water was transferred to the second test tube. The serial dilution was up to 10^{-9} mL. Thereafter, 0.1 mL of the 10^{-9} dilution series was transferred to the center of the surface of the nutrient agar plates; hence, the colony-forming unit (CFU) limit was 250×10^{-12} CFU/100 mL. The sample was evenly spread using a sterile L-shaped glass spreader and incubated at 37ºC for 24 h. The CFU was calculated and multiplied by the calculated dilution factor to determine the number of colonies in CFU/100 mL of the original sample.[25]

3. Results and discussion

3.1. Physiochemical and bacteriological characterization of Bagmati River water

The physiochemical and bacteriological measurements are essential to determine the river water quality. Physicochemical parameters, such as color, turbidity, conductivity, total hardness, pH, iron level, and chromium level, and biological parameters, such as MPN and SPC were measured accordingly (Table 1). The color of Bagmati River water at the Pashupati site (B-1) was brown, while that of the Balkhu site (B-2) in Kathmandu Valley was black (Figure 2). Turbidity indicates the presence of suspended solids, including both organic and inorganic substances, in the water. The turbidity was about 35.4 nephelometric turbidity units (NTU) at B-1 and 26.4 at B-2. The lower turbidity in the B-2 site validates the color of the water sample. The observed turbidity exceeded the World Health Organization's (WHO) recommended value.[26] The turbidity and color of the water suggested that before the confluence of the tributaries, the river water consisted of soil particles, which increased turbidity. However, after mixing with the tributaries, the soil particles disappeared, resulting in a transparent but black color. The black color is attributed to the mixing of sewer from either local sources or tributaries.[4,27]

Table 1. The Bagmati River water quality observed at Pashupati (B-1) and Balkhu (B-2) sites in Kathmandu Valley

Measured parameters	Site		WHO
	Pashupati (B-1)	Balkhu (B-2)	
Color	Brown	Black	Colorless
Turbidity (NTU)	35.4	26.4	5 – 10
pH	7.1	6.9	6.5 – 8.5
Total hardness (ppm)	62	104	500
Conductivity (μS/cm)	95.7	507	1500
Iron, Fe (ppm)	1.31	1.53	0.3
Chromium, Cr (ppm)	0.27	0.39	0.05
MPN/100 mL	1100	1100	Nil
SPC/100 mL	TMTC	TMTC	18×10^6

Note: The World Health Organization values are based on the standard recommended measurements[26].
Abbreviations: NTU: Nephelometric turbidity units; MPN: Most probable number; SPC: spread plate count; TMTC: Too many to count.

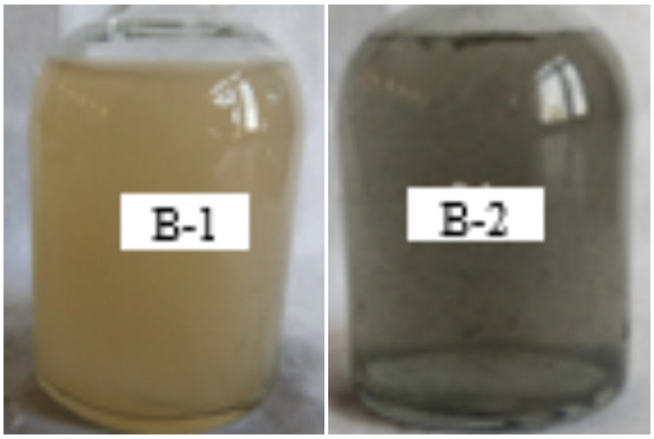

Figure 2. Water samples collected from the Pashupati site (B-1) and Balkhu site (B-2)

The pH observed was 7.1 at the B-1 site and 6.9 at the B-2 site. Both pH values were within the WHO[26] limit (i.e., 6.5 – 8.5) for drinking water, though water from B-2 was slightly acidic. The calcium and magnesium ions as bicarbonates, sulfates, and chlorides in the water are represented by hardness. The observed total hardness of the B-1 and B-2 sites was 62 and 104 ppm, respectively. Conductivity measures the conducting species from inorganic and organic substances in the water. Inorganic ions have higher mobility than organic ions, leading to a greater influence on conductivity.[28] The conductivity of the river water was very low (95.7 μS/cm) at B-1 sites; however, it was 5 times higher at the B-2 site (507 μS/cm). The higher conductivity downstream is attributed to the confluence of tributaries, and domestic effluent extensively increased the levels of conductive pollutants in the Bagmati River downstream. The observed concentration of iron and chromium at both observation sites was very high. The concentrations were more than 4 times higher than the WHO-recommended values (Table 1). The common biological pollutants are microorganisms. The MPN (total coliforms), calculated quantitatively in the river water samples, was 1100 (Table 1). The presence of coliform designates that the river water was polluted by fecal pollutants; hence, it is not safe for any domestic and agricultural use. The SPC indicates total bacterial counts, which were calculated quantitatively. The SPC of ten-fold serially diluted water samples was beyond the standard limit (i.e., it was too many to count [TMTC]). Both total coliforms and bacterial counts were extremely high in both observation sites, and both values were extremely high compared to the WHO limit (Table 1). From the observed water quality parameters, the river water was heavily polluted and cannot be used as it is for any domestic, agricultural, or industrial purposes. The heavily polluted Bagmati River water was treated using MO and CAMO.

3.2. FTIR spectroscopic analysis of MO seed extracts

The MO seed is a lignocellulosic material consisting of cellulose, hemicellulose, and lignin; its adsorption is mainly controlled by the surface functional groups of adsorbents. The treatment of water by MO is based on the adsorption of oppositely charged particles for charge neutrality that stabilizes the particles and binds with each other by a coagulation mechanism.[15] Hence, the surface functional groups in the adsorbents are important for the adsorption. The surface functional groups present on the surface of MO and CAMO were determined using FTIR spectroscopy (Figure 3). The peaks between 1750 and 1630 cm^{-1} represent C=O stretching. The carbonyl group may be partly bonded with fatty acids of lipids or amides of protein. The carbonyl peak of lipids was observed at 1750 cm^{-1}. The peak at 1650 cm^{-1} was due to the stretching of CN and the deformation of N-H in proteins. The high protein content (i.e., amide bonds) in the seeds contributes to N-H stretching. The peaks at 2850 and 2900 cm^{-1} in the spectra of both MO and CAMO correspond to symmetric and asymmetric C-H bond stretching. The intense peaks indicated the possible presence of predominating lipid components.

A comparison of FTIR spectra of MO and CAMO powder revealed a stronger stretching vibration band

Table 2. Effect of different concentrations of *Moringa oleifera* (MO) seed extract and citric acid-treated MO seed extract on remediation of microorganisms in B-2 water samples

Parameters	Before treatment	After treatment			
		MO seed extract (mg/L)			CAMO (mg/L)
		50	100	200	100
MPN/100 mL	1100	460	240	210	120
SPC/100 mL	TMTC	2.7×10^8	6.1×10^7	4.8×10^7	2.6×10^7

Abbreviations: MPN: Most probable number; SPC: Spread sheet count; CAMO: Citric acid-modified MO seed extract.

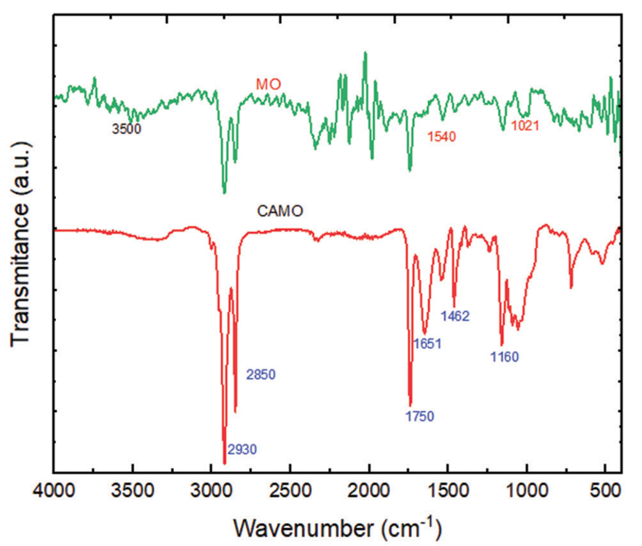

Figure 3. Fourier transform infrared spectra of *Moringa oleifera* (MO) and citric acid-treated MO seed powders

of the carboxyl group at 1750 cm^{-1} in CAMO than in MO, suggesting the esterification between the citric acid and alcohol groups of cellulose in the MO powder. The broad adsorptions between 2500 and 3500 cm^{-1} in CAMO confirmed the -OH bond stretching in lignin, protein, carbohydrate, and fatty acid. It is considered that polar groups, like -OH and -COOH, were added onto the surface of the bio-adsorbent on treatment with citric acid, which may considerably increase the cation exchange capacity and mechanical strength of the bio-adsorbent.[15]

3.3. Effect of different concentrations of MO seed extract on water remediation

The MO seeds consist of lignocellulose materials, mainly hemicellulose, cellulose, and lignin, with -COOH, -OH, and N-H functional groups. These functional groups can adsorb oppositely charged ions to form neutral particles that are responsible for the coagulation process.[29] The water treatment efficiency of MO was determined by treating water samples with seed powder extract. Water samples (B-1 and B-2) were treated with different concentrations of MO. The concentrations of MO used for the treatment were 50, 100, and 200 mg/L.

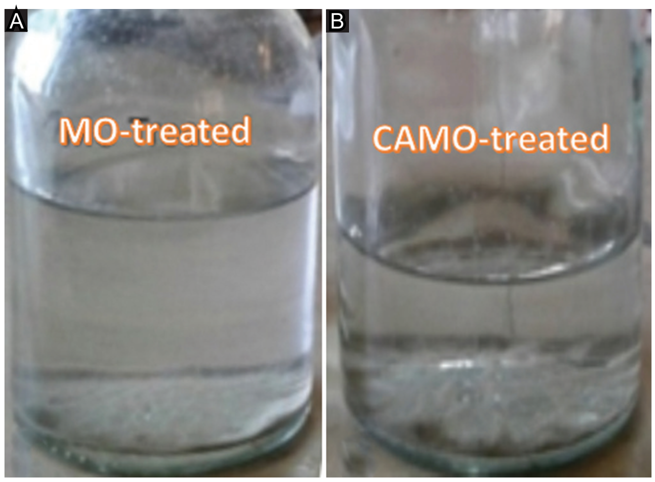

Figure 4. The river water samples after treatment with (A) *Moringa oleifera* seed extract (MO) and (B) citric acid-treated MO seed extract

3.3.1. Physicochemical remediation of river water

On treatment, the highly turbid grey-colored water sample (B-1) and polluted black-colored water sample (B-2) became colorless and clean after treatment with MO (Figure 4). The change in color and turbidity suggested that MO is useful for removing suspended particles even from heavily polluted river water. The efficiency of suspended particle removal from the water samples was distinctly observed in the turbidity measurement. As aforementioned, the turbidity of the B-1 sample was 7 times higher and that of the B-2 sample was 5 times higher than the WHO recommended value. After treatment, turbidity was drastically reduced to 4.1 NTU, which is below the WHO-recommended value, even at a low concentration (50 mg/L) (Figure 5A). The turbidity reduction efficiency of MO increases with increasing concentrations, from 50 to 200 mg/L. The turbidity reduced to <3.1 NTU after treatment with 200 mg/L MO in both water samples. This result

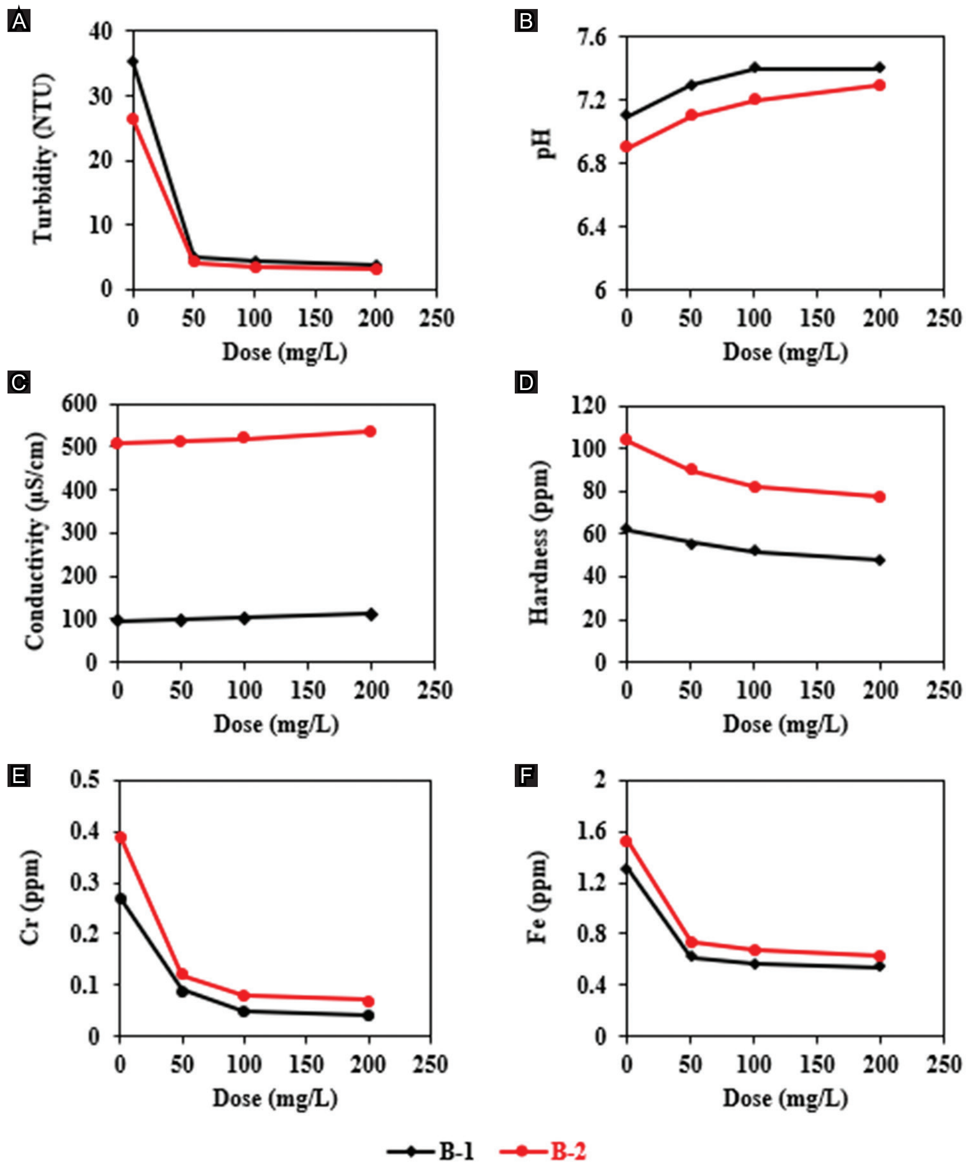

Figure 5. Effect of different concentrations of *Moringa oleifera* seed extract on (A) turbidity, (B) pH, (C) conductivity, (D) hardness, (E) chromium levels, and (F) iron levels in water samples B-1 (blue) and B-2 (red)

ascertained the clean and transparent water observed in the treated water (Figure 4). Ndabigengesere *et al*.[30] suggested that turbidity reduction was due to a destabilization mechanism. The stirring of sample water containing MO distributes cationic protein in the water body. The small-sized, positively charged MO particles interact with suspended particles and adsorb negatively charged particulates from polluted water for charge neutrality.[31] Such interactions disturb the binding forces, precipitating small particulates by coagulation.[18,32,33] The results indicate that MO is a natural coagulant capable of efficiently removing suspended particles almost completely, even from severely polluted river water.

The pH is an important factor affecting coagulation.[32] The pH of treated B-1 water samples was slightly increased for 50 mg/L MO and remained relatively constant for 100 mg/L MO. After treatment with MO, both the water samples (B-1 and B-2) became slightly alkaline; 7.3 for B-2 and 7.4 for B-1 sample (Figure 5B). The slight increase in pH of the treated water samples indicates the soluble cationic proteins in the seeds.[32] The basic amino acids of MO absorb protons from water and release hydroxyl groups, changing the slightly acidic water to a slightly basic pH.[9] Water treatment with MO slightly increased the conductivity with increasing MO concentration in the water samples (Figure 5C).

However, the hardness was decreased with increasing MO concentration (Figure 5D), which could be attributed to adsorption and inter-particle bridging.[29] After water treatment, lightweight solids/flocs were observed, which may be precipitation of soluble carbonate and bicarbonate ions, causing a reduction of hardness.[9]

Heavy metals are environmental pollutants of particular concern due to their toxicity.[18] The non-biodegradable and persistent properties of heavy metals pose serious ecotoxicological problems, with mutagenic, genotoxic, teratogenic, and carcinogenic effects on human health. The efficiency of heavy metal removal using MO was determined by measuring iron and chromium concentrations in the river water samples (B-1 and B-2) treated with different MO concentrations. The concentrations of iron in both samples were more than 4 times higher than the WHO standard. After treatment, the iron concentration was reduced to 0.62, 0.56, and 0.54 ppm at 50, 100, and 200 mg/L of MO, respectively, for the B-1 water samples. Similarly, in the B-2 water samples, the iron concentration was reduced from 1.53 ppm to 0.74, 0.68, and 0.62 ppm at 50, 100, and 200 mg/L, respectively (Figure 5E). It was reported that MO seeds consist of glucosinolates and phenolics (flavonoids, anthocyanins, proanthocyanidins, and cinnamates). The central carbon atoms of each glucosinolate are bonded to the thio-glucose group through a sulfur atom, forming a sulfate ketoxime, and are also bonded to a sulfate group via a nitrogen atom. These functional groups that contain sulfur and nitrogen are responsible for good metal reduction in river water.[15]

The concentration of chromium in the river water samples was more than 5 times higher than the WHO standard. After treatment with MO, the concentration of chromium was decreased from 0.27 ppm to 0.09, 0.05, and 0.04 ppm, with increasing coagulant concentrations of MO of 50, 100, and 200 mg/L, respectively, for B-1 river water samples (Figure 5F). Similarly, in B-2 water samples, the concentration of chromium was reduced from 0.39 ppm to 0.12, 0.08, and 0.07 ppm with increasing coagulant concentrations of 50, 100, and 200 mg/L, respectively (Figure 5F). It was observed that the concentrations of chromium in river samples were drastically reduced to the acceptable standard value using MO. This could be due to the presence of amphoteric proteins in MO seeds that bind to oppositely charged metal ions, leading to metal precipitation. Since metals are present in dissolved or particulate forms, they can exist as free hydrated ions or as complex ions chelated with inorganic ligands, such as chlorides and carbonates, or organic ligands, such as amines, humic or fulvic acids, and proteins. It is considered that the small-sized charged particles in MO seeds interact with suspended particles and bond with oppositely charged metal ions, forming coagulants and removing metal ions by filtration.[18,32-34]

3.3.2. Bacteriological remediation of river water

The river is unsafe for drinking and other domestic uses because it is highly contaminated with microorganisms. The microbial load on polluted river water was very high and beyond the limit of measurement. After river water treatment, the microbial concentration drastically decreased with increasing MO concentration, (50 – 200 mg/L) (Table 2). It was observed that 100 mg/L MO decreased the microbial load by up to 78.18%, even for heavily polluted river water samples (B-2). The microorganisms identified from SPC were *Escherichia coli* and *Klebsiella* species. There was a reduction in the microbial load of both species. After treatment, the bacterial colonies were reduced to 4.8×10^7 from an infinite number (i.e., TMTC). With proper mixing of MO and contaminated water, the particles were enlarged, and flocs were formed that settled at the bottom of the vessel. The results indicate that MO seeds have good coagulation properties, which are useful to treat heavily polluted river water.[32] Although there was a drastic decrease in MPN counts in treated water, the count was still above the limits of WHO standards. Hence, further treatment is suggested for the complete removal of microbiological pollutants with higher doses of MO. It was reported that the active compound 4-alpha rhamnosyloxy-benzyl isothiocyanate, known as glucosidal mustard oil, coagulates solid matter, including suspended bacteria, and facilitates their easy removal.[9]

3.3.3. Comparison of efficacy of MO and citric-acid-treated MO seed extracts on water treatment

The bioremediation efficiency of MO powder was enhanced by modifying the surface morphology with citric acid. Chemical treatment increased the surface area, thereby improving its adsorption capacity. The removal/reduction efficiencies of MO and CAMO were compared by treating polluted river water samples (B-1 and B-2) using 100 mg/L extracts. The comparative results of bio-remediation of turbidity, total hardness, and heavy metal (Fe and Cr) concentrations of both river water samples are displayed in Figure 6A and B. The treatment efficiency of CAMO was higher than that of MO. The turbidity reduction efficiency of MO was 87.57% and 87.12% for B-1 and B-2 samples, respectively. The efficiency was higher at 93.78% and

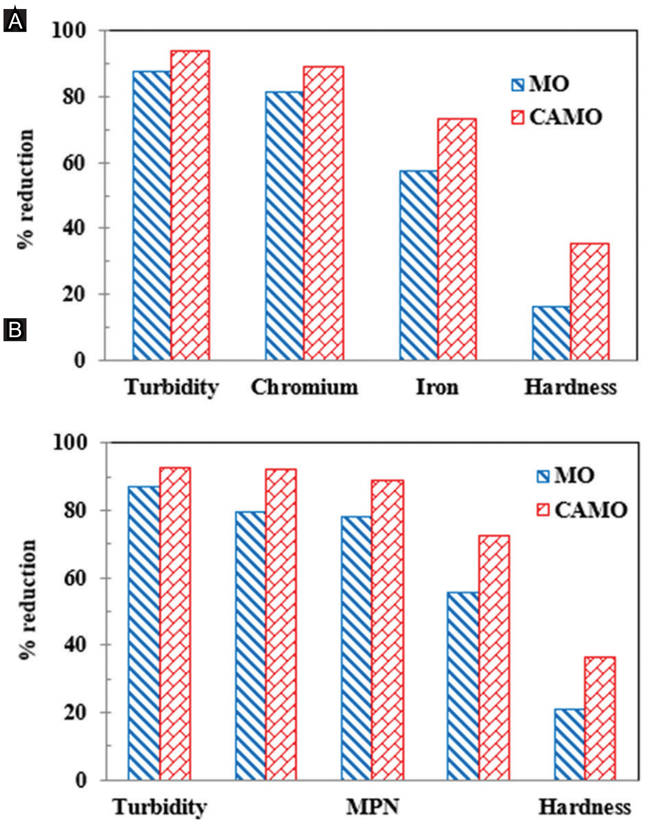

Figure 6. Percentage removal/reduction of turbidity, heavy metals, and hardness using *Moringa oleifera* (MO) and citric acid-treated MO seed extracts in water samples from (A) Pashupati (B-1) and (B) Balkhu (B-2) sites

92.80%, respectively, when treated with CAMO. There was a 57.2% and 55.5% reduction in iron concentration in B-1 and B-2 samples treated with MO; the reduction was more than 70% in both water samples when treated with CAMO. Similarly, the removal efficiency of chromium was up to 90% for CAMO treatment and approximately 80% for MO treatment. The hardness reduction efficiency of CAMO was also higher than that of MO for both the river water samples B-1 and B-2. The MPN and SPC were reduced by more than 2 times for CAMO treatment than that for MO in the B-2 river water sample (Table 2). Taken together, the results suggest that MO efficiently reduces turbidity, heavy metals (iron and chromium), and microorganisms from polluted river water. The chemical treatment of MO enhances metal removal capacity and other bio-remedial activity by developing efficient adsorption sites to increase coagulation activity. Therefore, chemical modification increases the surface areas and adsorption sites, thereby enhancing the coagulation ability of MO and the uptake of pollutants from water.[19]

4. Conclusion

The Bagmati River water is excessively polluted with physicochemical and microbial pollutants, which were more pronounced after the mixing of tributaries. The color, turbidity, heavy metal concentration (chromium and iron), MPN, and SPC exceeded the WHO limit. MO (200 mg/L) reduced turbidity by up to 89.54% in B-2 water samples, transforming the black-colored water into clear and transparent. CAMO reduced turbidity by 93.78% in B-1 water samples and by 92.80% in B-2 water samples. The removal efficiency of heavy metals by CAMO was 73.238% for Fe and 92.30% for chromium. Similarly, there was a progressive decrease in coliform counts, MPN, and SPC, with increasing concentrations of MO. After treatment with CAMO, the heavily polluted turbid river water became clean and clear (i.e., within WHO standards). The results collectively suggest that CAMO remediated the heavily polluted river water more effectively than MO (i.e., without citric acid treatment) at 100 mg/L, although both extracts are effective coagulants and bio-adsorbents in water treatment. Despite the necessity for further investigations regarding purification on a pilot scale, the analytical results suggest that MO seed extracts are effective in treating the Bagmati River water on a small scale, providing clean and clear water. MO seed extracts are useful as an eco-friendly, economical, non-toxic, and simple natural coagulant for the purification of highly polluted and microbiologically contaminated water.

Acknowledgments

Authors are thankful to the University Grants Commission, Nepal for their support.

Funding

This research was partially supported by the University Grants Commission, Nepal, through the Collaborative Research Grants (CRG-79/80-S and T-01).

Conflict of interest

The authors declare no competing interest.

Author contributions

Conceptualization: All authors
Investigation: Manisha Neupane
Methodology: Manisha Neupane

Writing – original draft: Manisha Neupane
Writing – review & editing: Mandira Pradhananga Adhikari.

Availability of data

Data are available from the corresponding author on reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 52-66.
doi: 10.36922/AJWEP025050027

ORIGINAL RESEARCH ARTICLE

Decoding carbon sequestration: The impact of agriculture, conservation policies, climate, and land use

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Received: January 29, 2025; Revised: February 20, 2025; Accepted: February 25, 2025; Published Online: March 11, 2025

Abstract: Pakistan's forests play avital role in mitigating climate change by absorbing and storing carbon dioxide from the air, making them essential natural carbon sinks. Achieving a balance between logging and forest preservation is necessary for the country to meet global climate goals. This study employs a robust least squares regression approach to identify the components of carbon sequestration, using quarterly time series data from 1990 Quartile 1 to 2023 Quartile 4. The findings show that agricultural income, forest preservation legislation, rainfall variability, high temperatures, and land-use changes significantly affect carbon sequestration in Pakistan. Positive changes in forest cover highlight the need for continuous afforestation and replanting efforts. However, a decline in forest carbon sink capacity due to agricultural output and land-use changes hampers climate change mitigation. The results emphasize the delicate balance between economic growth and environmental conservation. These findings suggest that addressing the challenges of climate change and land use requires specialized policies that prioritize forest conservation while managing economic costs.

Keywords: Carbon storage potential; Sustainable forestry; Ecosystem resilience; Land management strategies; Climate variability; Environmental policy; Pakistan

1. Introduction

Globally, forests cover 4.06 billion acres or 31% of the Earth's land area.[1] They play a vital role in mitigating climate change by absorbing and storing carbon dioxide, thereby slowing the pace of global warming.[2] In Pakistan, maize is cultivated extensively in both rainfed and irrigated areas. Agriculture and forest management contribute to climate change mitigation by improving soil organic carbon through carbon sequestration.[3] Circular economy approaches have further enhanced forest management by promoting sustainable land use and carbon sequestration. The Forest Carbon Benefit Indicator (FCBI) estimates the financial and ecological advantages of carbon sequestration in Pakistan's forests, along with the outcomes of conservation activities. Pakistan's efforts to minimize greenhouse gas (GHG) emissions, promote long-term carbon sequestration, and understand the influence of agricultural income on the carbon-protective function of forests are closely interconnected. Forest conservation methods, such as reforestation and establishing protected areas, are crucial for sustainable development.[4] This study explores the complex relationship between climate and carbon sequestration in these ecosystems. Given Pakistan's rapidly urbanizing population, understanding the demographic impact on forests and carbon sequestration is essential for addressing climate change. Urbanization and agricultural expansion significantly affect Pakistan's forest ecosystems and their capacity to sequester carbon, making sustainable land management vital for mitigating climate change.[5] Carbon sequestration is a key strategy in reducing global warming, as forest ecosystems not only absorb but also release carbon dioxide. Pakistan's 23.8 million hectares of fertile land are heavily used for agriculture. The Indus River and its tributaries support an irrigated agricultural sector encompassing 14.6 million hectares across Punjab, Sindh, and Khyber Pakhtunkhwa.[6]

Forest carbon stocks in the country have declined from 668 gigatons in 1990 to 662 gigatons in 2020, while carbon density increased from 159 to 163 tons per hectare.[7] Climate change, driven by rising GHG concentrations, is one of the most significant challenges of our time. A major global issue is fostering economic growth while simultaneously reducing GHG emissions, particularly carbon emissions.[8] Pakistan's economy has shifted from agriculture to industry, and this industry-led growth led to increased energy consumption and pollution.[9] He and Deng[10] found that natural resource quantities, mineral rents, and forest rents affect global finance unevenly. Forestry, fisheries, livestock, and crops are major agricultural subsectors in Pakistan, as they provide employment and income for low-income and disadvantaged families. Over half of the workforce and 62% of rural residents depend on agriculture for their livelihoods. However, Pakistan faces water shortages, low agricultural and livestock production, low wages, and extreme food insecurity.[11] Deforestation contributes to carbon emissions, exacerbating environmental issues and global warming. Since 1990, deforestation has resulted in the loss of 420 million acres of forest worldwide, although the rate has slowed. By 2020, the rate of deforestation was predicted to decrease to 10 million hectares per year, down from 12 million hectares between 2010 and 2015. Pakistan is combating the "Timber Mafia," a criminal group that illegally chops down and sells trees. Khalid *et al.*[12] found that illegal wood harvesting is four times higher than legal timber extraction. From 1990 to 2000, Pakistan lost 41,100 hectares of forest annually,[13] with an average annual deforestation rate of 1.63%. From 1990 to 2005, Pakistan lost 625,000 hectares, or 24.7% of its forest cover.[14] Forests in Pakistan now cover just 2.5% of the country, with deforestation occurring at 2.1% per year. This deforestation has hindered Pakistan's ability to meet the World Bank's Millennium Development Goal of increasing forest cover from 2.5% to 6% by 2015.[15] To mitigate deforestation, Pakistan has implemented various laws and initiatives aimed at conserving and expanding forest cover. With a deforestation rate of 4.6%, Pakistan ranks second globally in terms of deforestation. Forest managers and policy makers have long been concerned about the depletion of resources caused by human activity. Reforestation is essential in the fight against climate change and global warming.[16]

Without more and better-protected areas, sustainable growth is unattainable.[17] Pakistan needs to adopt sustainable forestry practices, such as plantation drives, to achieve long-term economic growth and mitigate climate change.[18] Globally, forests encompass 726 million acres of protected areas, with South America being unique among the world's six regions, as31% of its forests are protected.[19] Since 1990, the global forest cover in protected areas has expanded by 191 million hectares; however, it decreased between 2010 and 2020.[20,21] To safeguard both the environment and economy, Pakistan requires green mechanization in agriculture, sufficient investment in research and development, and integrated policies that promote economic development alongside environmental protection.[22] Integrated landscape solutions aimed at "reducing emissions from deforestation and forest degradation" (REDD+) are receiving increasing attention and funding.[23] Globally, multiple protected zones are being established to mitigate human-caused biodiversity loss. In Khyber Pakhtunkhwa, a province in Pakistan, free plants are now being provided for agroforestry and agricultural forestry.[24] Public forestry extension agents monitor the Billion Trees Afforestation Project (BTAP), which will continue under the newly announced 10-BTAP Project by the Government of Pakistan in 2023.[25]

Since 2000, the global average daily temperature has never exceeded 1.5°C above pre-industrial levels.[26] Long-term fluctuations in annual rainfall and temperature, mainly driven by meteorological changes, may lead to floods and droughts.[27] Climate change is influenced by factors such as temperature, precipitation, humidity, carbon dioxide levels, air pollution, wind, and atmospheric pressure.[28] In hyper-arid and arid regions, droughts are common during the winter monsoon season (December – February) due to decreased seasonal rainfall and rising temperatures, which increase evapotranspiration.[29] Ahmed *et al*.[30] found that Pakistan's surface temperature rose by 0.1°C per decade from1960 to 2010, accompanied by highly variable precipitation patterns. Since 1990, private ownership of forests has increased, while public woodlands have decreased. China, Russia, Brazil, and Canada together own 54% of the world's forests, with the United States, Canada, and Russia collectively holding 46%. Heat waves – defined as annual temperatures of 29°C or higher – would affect approximately 5 times fewer people if global warming were limited to 1.5°C instead of 2.7°C. By the end of the century, climate change could force 3 – 6 billion people – roughly one-third to one-half of the global population, out of the habitable zone, leading to extreme heat, food shortages, and increased mortality.[31] Pakistan's land cover change maps show that most agricultural expansion is primarily occurring in rangeland and forest areas. Land use changes in Pakistan are driven by both economic growth and population growth.[32] Understanding the impact of urbanization and land use on regional and local climate, ecosystem services, biodiversity, and ecosystem functioning is essential. To balance climate change and food security, effective carbon sequestration – particularly land-based sequestration – is crucial.[33]

The preceding discussion raises the following research questions: First, what is Pakistan's forest cover-based carbon sequestration capacity? To achieve better carbon stewardship and climate change mitigation for sustainable development in Pakistan, it is crucial to understand its carbon sequestration potential. This knowledge will facilitate the development of policies and programs aimed at addressing these challenges. Second, how effectively have afforestation initiatives and protected area projects in Pakistan promoted long-term forest management and carbon sequestration? This question examines the effectiveness of forest management and conservation policies, particularly in protected areas and reforestation initiatives, to better understand their impact on carbon sequestration, sustainable practices, long-term environmental resilience, and biodiversity conservation in Pakistan. Finally, how do Pakistan's forests contribute to GHG reduction? This inquiry may reveal the factors that influence the carbon-capturing and carbon-storing potential of Pakistan's forests, which could guide strategies to enhance the country's climate change mitigation. The objectives of this study are as follows:

(i) To analyze Pakistan's FCBI, which assesses its forests' carbon sequestration capacity and their role in carbon management.
(ii) To evaluate the success of forest preservation and management initiatives, such as afforestation and protected areas, in enhancing carbon sequestration, and aligning with the Sustainable Development Goals.
(iii) To assess how agricultural income, annual deforestation rates, climate, population, and land use changes affect Pakistan's forest carbon sequestration capacity.

This research employs a robust least squares (RLS) regression technique that accounts for model outliers, ensuring accurate parameter estimations. The methodology enhances statistical rigor by identifying the most significant influencing factors. The research framework is structured as follows: Section 2 provides the literature review; Section 3 outlines the theoretical development; Section 4 presents the data and methods; and Sections 5 and 6 present the findings and conclusions, respectively.

2. Literature review

Environmental experts have studied the socioeconomic and environmental factors influencing forest carbon sequestration for decades.[34-36] It has long been recognized that forests are important "carbon sinks" that store substantial amounts of carbon dioxide.[2,37] Forests absorb 30% of the world's carbon dioxide emissions, helping to decrease climate change. Earlier studies have emphasized the need to preserve and expand forests to mitigate climate change.[38,39] However, most of these studies have focused on industrialized countries, then overlooking the unique dynamics of developing nations, where deforestation, land-use changes, and socioeconomic pressures pose significant challenges to forest management.[40,41] This study uses Pakistan as a case example of a nation where carbon sequestration capacity is substantially influenced by economic, environmental, and climatic factors. The academic literature also discusses how growing affluence and agricultural expansion contribute to deforestation and carbon sequestration.[42,43] Saleem *et al.*[44] demonstrated that deforestation is primarily driven by the conversion of forests into agricultural land and pastures. This issue is particularly important in developing countries like Pakistan, where agriculture is the primary livelihood. This study empirically investigated how increasing agricultural income affects carbon sequestration, emphasizing the need for sustainable farming. Deforestation, another key factor, has been extensively studied. Bajoria *et al.*[45] demonstrated that global deforestation poses a serious threat to biodiversity, global warming, and carbon sequestration. Kinda and Thiombiano[46] argue that economic pressures and poor governance lead to deforestation in developing countries. Secondary forest growth may temporarily increase carbon sequestration after deforestation.[47]

Temperature and precipitation are crucial factors affecting forest carbon sequestration. Liu *et al.*[48] found that the carbon storage capacity of forests diminishes as temperature rises due to increased respiration and reduced biomass growth. Irregular precipitation patterns can also induce water stress, which harms forests.[49] Most prior studies have focused on temperate or boreal forests, overlooking issues specific to tropical and subtropical regions such as Pakistan.[50,51] This study showed how increasing temperatures and variable rainfall patterns have impacted carbon sequestration in Pakistan's forests, contributing to the global literature. It also underscores the importance of climate-resilient forestry practices tailored to local conditions. A large body of research has examined land-use dynamics and their environmental impacts, highlighting how land-use changes affect carbon sequestration.[52,53] Jiang *et al.*[54] and Ersoy Tonyaloğlu[55] found that urbanization and agricultural development reduce forest cover and carbon storage capacity. These studies emphasize the need for integrated land-use planning to balance economic growth and environmental sustainability. However, the literature has yet to explore how land-use changes, combined with meteorological, socioeconomic, and other factors, impact national carbon sequestration levels. This gap is addressed in this study, which analyzes the effects of land-use changes, agricultural income, and climate on carbon sequestration in Pakistan. Policy interventions to improve forest carbon sequestration in developing countries are underexplored. Mori[56] and Grant and Le Billon[57] suggest that REDD+ initiatives could promote sustainable forest management. Pakistan, however, faces challenges in implementing such programs due to institutional weaknesses, limited funding, and sociopolitical constraints. The study highlights the negative effects of agricultural income, temperature, and land-use changes, as well as the potential benefits of reforestation, which should inform policy makers seeking to promote carbon sequestration while fostering economic growth. By integrating economic, environmental, and meteorological factors, this study evaluates Pakistan's forest carbon sequestration potential. Although understanding of these processes has improved, significant gaps remain, particularly in rapidly developing countries like Pakistan, where economic growth and environmental sustainability are often in conflict. This research aims to assist practitioners and policy makers in enhancing carbon sequestration and mitigating climate change, while expanding the theoretical understanding of the complex relationship between socioeconomic, environmental, and climatic challenges.

The literature review led to the formulation of the study's research hypotheses:

H1: Increased agricultural revenue in Pakistan diminishes carbon sequestration

The agricultural sector in Pakistan is essential to the country's economic growth due to its contributions to employment and Gross domestic product. However, increased agricultural activity often leads to deforestation and land-use changes, which adversely affect carbon sequestration. As agricultural income rises, farmers and agribusinesses may convert forests in to croplands or pastures to increase production, thereby reducing carbon dioxide absorption. Practices such as mono cropping and the use of chemical fertilizer scan de grade soil quality and carbon storage. This hypothesis examines the tension between the economic benefits of agriculture and environmental sustainability, proposing policies that encourage sustainable land-use practices and safeguard the carbon sequestration potential of forests.

H2: Land-use shifts and afforestation may mitigate the carbon sequestration losses caused by deforestation

Deforestation is a major source of carbon loss, a sit depletes the carbon sink capacity of forest ecosystems and releases stored carbon into the atmosphere. The relationship between carbon sequestration and deforestation is not necessarily linear. Controlled land-use transitions, afforestation, and secondary forest regeneration can help restore carbon storage capacity following deforestation. Deforested land can be converted into sustainably managed plantations, agroforestry systems, or protected afforestation zones to recover a portion of the carbon sequestration potential.

However, these compensatory processes are typically insufficient and offer only temporary relief from widespread deforestation. Thus, this hypothesis aims to determine whether deforestation trends in Pakistan are accompanied by adequate reforestation and forest management practices that mitigate carbon losses or whether the continued degradation of Pakistan's forest cover further diminishes its ability to store carbon.

H3: Rising temperatures and unpredictable rainfall reduce Pakistan's carbon sequestration

The study suggests that high temperatures and variable precipitation negatively affect the health of forests, reducing their biomass production and making them less effective carbon sinks.

Carbon sequestration and the role of forests in mitigating climate change are topics of ongoing research. However, numerous questions remain, especially for developing countries like Pakistan.[58,59] Local socioeconomic and environmental factors significantly influence carbon sequestration, yet most studies focus on global trends or regional assessments, neglecting the specific dynamics at play in individual countries.[60,61] Many studies fail to consider the complex interactions between climatic factors, land-use changes, deforestation rates, and agricultural practices that shape carbon dynamics.[52,62] Pakistan, with its high rates of deforestation, unsustainable farming practices, and vulnerability to climate change, faces unique challenges that are often overlooked in global and regional research.[63,64] There is a lack of country-specific research on the policy-relevant impacts of socioeconomic factors on forest carbon benefits in Pakistan, which hinders the development of effective, evidence-based strategies for carbon sequestration.

This study addresses these gaps in understanding Pakistan's forest carbon sequestration capacity by examining the factors that affect it. The study incorporates agricultural income, deforestation rates, temperature, precipitation, and land-use improvements to present a comprehensive picture of carbon sequestration processes. Unlike previous research that treated these factors in isolation, this study examines their combined impact on carbon sequestration.[65,66] It also provides valuable data from Pakistan, which has been largely overlooked in international research on forest carbon dynamics, despite facing major concerns from deforestation and climate change.

The research advances theoretical understanding by linking its findings to economic and environmental concepts. It supports the environmental sustainability theory of carbon sequestration and deforestation, demonstrating how economic growth can degrade the environment but also how income and conservation efforts can promote sustainability.[67] The study also high light show theories of land-use change and agricultural growth affect carbon sequestration in Pakistan.[68] These theoretical contributions provide the groundwork for future research in other developing countries with similar environmental, social, and economic conditions, enhancing our understanding of carbon dynamics.

From a policy perspective, the study provides practical insights that bridge theoretical research to real-world applications. By illustrating how agricultural income and land-use changes diminish carbon sequestration, it advocates for sustainable farming practices and urban planning. The study also suggests targeted deforestation management strategies and climate-resilient forestry actions to improve carbon sequestration while balancing economic growth. Given its comprehensive approach and focus on Pakistan, this study is valuable for researchers, policymakers, and international organizations working on climate change and environmental degradation. It fills significant gaps in the literature and provides guidance for future research and policy development in this critical field.

3. Data source and methodology

Table 1 presents the variables used in the study. The time-series data were collected from the World Bank[69] and the Climate Change Knowledge Portal.[70] In addition, the data were converted into quarterly intervals, covering the period from 1990 Quartile 1 to 2023 Quartile 4.

The social-ecological systems theory helps explain the interaction between forest ecosystems and human systems, including social policies and activities.[71] Activities such as farming, development, tree cutting, and preservation have significant ecological impacts on forests. According to this theory, forests thrive through the dynamic interactions between human and natural systems.[72] Policies and initiatives that promote reforestation and establish protected areas directly influence forests' carbon sequestration capacity. The social-ecological systems theory also supports adaptive governance, which fosters sustainable policies through feedback loops between human and natural systems.[73] This theory aids in the sustainable and ethical management of forests by understanding how social, political, economic, and environmental factors affect carbon sequestration. Environmental determinism posits that climate, terrain, and resources shape human

Table 1. List of variables

Variable type	Variable name	Symbol used	Measurement/formula	Unit	Data source
Dependent variable	Carbon sequestration capacity	FCBI	(Forest rents as % of GDP-net forest depletion as % of GNI)/CO_2emissions (metric tons per capita)	Index (dimensionless)	World Bank[69]
Independent variables	Agricultural income	AGRINC	Agriculture, forestry, and fishing value added (current USD)	USD (current)	World Bank[69]
	Annual deforestation rate	DEFORATE	([Forest area year 2 -forest area year 1]/forest area year 1)×100	Percentage (%)	World Bank[69]
	Forest management and conservation policies	FMCP	(Forest rents as % of GDP+Agricultural value added as % of GDP)/R&D expenditures as % of GDP	Index (dimensionless)	World Bank[69]
	Climatic variables — temperature change	TEMP	Annual mean temperature change	Degrees Celsius (°C)	CCKP[70]
	Climatic variables — rainfall	RAINFALL	Annual total precipitation	Millimeters (mm/year)	CCKP[70]
	Population and land use change — urban population	URBANPOP	Urban population as a percentage of total population	Percentage (%)	World Bank[69]

Abbreviations: CCKP: Climate Change Knowledge Portal; CO2: Carbon dioxide; FCBI: Forest Carbon Benefit Indicator; GDP: Gross domestic product; GNI: Gross national income; R&D: Research and development; USD: United States dollars.

behavior, social development, and economic activities.[74] This concept is critical for understanding how plants store carbon in response to climate change. Temperature and precipitation regulate plant growth, soil fertility, and carbon sequestration, among other ecological processes. Moderate temperatures and abundant rainfall enhance forest carbon storage, while extreme heat waves and droughts reduce forest productivity and contribute to deforestation.[75] Human efforts to maintain and conserve forests are influenced by climate and geography,[76] particularly through factors such as urbanization, land use, and agriculture. This hypothesis can guide researchers in studying how environmental factors affect forest carbon sequestration and how societies have adapted to these constraints through sustainable policies and practices.

The study employed an analytical model to provide statistically robust insights into forest carbon benefits and critical socioeconomic and environmental challenges. RLS regression was used for empirical estimations. RLS regression effectively manages outliers and heteroskedasticity in complex datasets, making it especially useful when ordinary least squares (OLS) assumptions are violated.[77] Unlike OLS, which minimizes the sum of squared residuals, robust regression utilizes several optimization methods to reduce the influence of outliers on model predictions. As a result, RLS provides more reliable and unbiased parameter estimates for datasets with non-normal error distributions or extreme values.[78] This technique is particularly valuable when studying carbon sequestration, agricultural income, deforestation, forest management, climatic factors, and land use changes. In an OLS model, outliers often include extreme meteorological variables, such as precipitation and temperature, or rapid changes in forest cover, such as deforestation. The RLS approach improves the model by reducing extreme values, providing a clearer presentation of variable patterns and correlations.[79]

Environmental and socioeconomic variables typically exhibit varied error rates; therefore, robust regression accounts for this error.[80] Through the use of iteratively reweighted least squares, robust regression updates data weights, reducing the influence of observations with higher residuals to stabilize model fit. Despite such variations, robust regression ensures the validity of the study. Minimizing the impact of outliers in population growth, land use, and carbon sequestration policy outcomes improves accuracy. **Equation I** presents the RLS equation for reference:

$$FCBI = \Omega_0 + \Omega_1 AGRIINC + \Omega_2 DEFORATE + \Omega_3 FMCP + \Omega_4 TEMP + \Omega_5 RAINFALL + \Omega_6 URBANPOP + \varepsilon \quad (I)$$

Where:
FCBI = Forest Carbon Benefit Indicator;
AGRINC = Agricultural income;
DEFORATE = Deforestation;
FMCP = Forest management and conservation policies;
TEMP = Extreme temperature;
RAINFALL = Rainfall vulnerability;
URBANPOP = Urban population; and
ξ = Disturbance term.

RLS regression improves empirical validity and reduces bias by adhering to quantitative research standards for handling data outliers.[81] It provides a comprehensive and systematic assessment of the interrelationships between study variables, leading to practical, evidence-based solutions for sustainable forest management and climate change mitigation.

4. Results and discussion

Table 2 presents the descriptive statistics for the variables. In Pakistan, the FCBI fluctuated between 0.464 and 5.660 metric tons of carbon dioxide per year, with a mean value of 1.940 metric tons. Agriculture income improved carbon benefits by increasing the FCBI by 3,740 US dollars. The annual deforestation rate varied from 0.473% to 1.636%, with an average of 0.974%, placing pressure on forest carbon sequestration. The forest sustainability index trends fluctuated over the analyzed period, with an average of 4.780 US dollars, showing a decrease of 1.060 US dollars. Weather factors, such as temperature and rainfall, strongly influenced the FCBI. Forest carbon sequestration was affected by the average temperature increase of 0.567°C and annual precipitation of 293.558 mm. The average urban population was 6,110, with a range from 3,528 to 8,897. Urbanization patterns shifted and altered forest ecosystems and land use. The extreme values of each variable demonstrated the range of variability within the dataset. Kurtosis, skewness, and standard deviation provided insights into data distribution, symmetry, and dispersion. A kurtosis of 5.150 suggests a distribution with heavy tails and a large peak, whereas the FCBI's skewness of 1.574 indicates a right-skewed distribution.

Figure 1 illustrates the influence statistics. These statistics revealed outliers and impactful observations within the dataset. The R Student and difference in fit(s) methods identified two extreme outliers that notably affected the regression analysis. The Hat Matrix approach also identified two highly leveraged observations that may significantly influence the regression findings. In addition, COVRATIO detected another outlier in the dataset. Given these results, RLS regression was the optimal choice for obtaining robust estimates.

Table 3 presents the RLS estimates. The results indicated a negative association between FCBI and agricultural income. As agricultural income increased, woodland carbon sequestration decreased. This conclusion emphasizes the conflict between forest protection and agricultural growth. Farming often leads to deforestation to make way for crops or livestock, reducing forest cover and carbon stored in soil and woody plants.[82] Agricultural activities such as soil tilling and fertilizer application release carbon into the atmosphere.[83] Pakistan, with an economy heavily dependent on agriculture, faces significant challenges in balancing economic growth and environmental sustainability.[84]

Table 2. Descriptive statistics

Methods	FCBI	AGRINC	DEFORATE	FMCP	TEMP	RAINFALL	URBANPOP
Mean	1.940	3.740	0.974	4.780	0.567	293.558	6110
Maximum	5.660	8.380	1.636	9.820	1.423	442.880	8897
Minimum	5.464	1.190	0.473	1.060	-0.375	181.500	3528
Std. dev.	1.390	2.480	0.171	2.980	0.475	64.984	1615
Skewness	1.574	0.427	0.923	0.298	-0.191	0.149	0.027
Kurtosis	5.150	1.766	9.793	1.594	2.481	2.215	1.787

Source: Authors' estimate. Abbreviations: AGRINC: Agricultural income; DEFORATE: Deforestation; FCBI: Forest Carbon Benefit Indicator; FMCP: Forest management and conservation policies; RAINFALL: Rainfall vulnerability; Std. dev.: Standard deviation; TEMP: Extreme temperature; URBANPOP: Urban population.

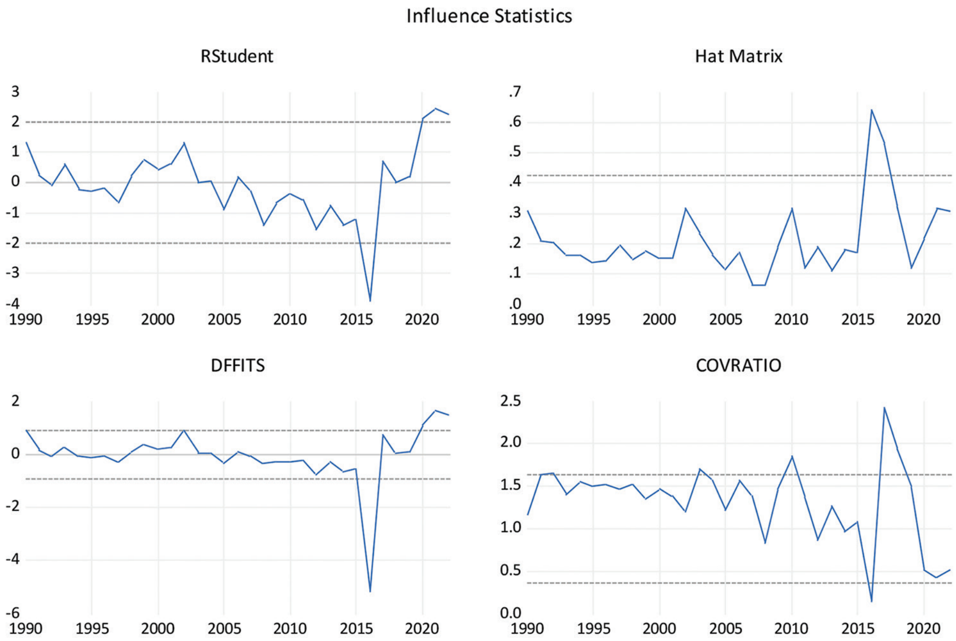

Figure 1. Influence statistics

Source: Authors' estimates. Abbreviation: DFFITS: Difference in fit(s).

Table 3. Robust least squares regression estimates

Dependent variable: FCBI				
Method: Robust least squares				
Variables	**Coefficient**	**Standard error**	**z-statistic**	**Prob.**
AGRINC	−0.0029	0.0002	−9.8422	0.0000
DEFORATE	3.5900	74,885	4.7960	0.0000
FMCP	−0.0004	0.0002	−1.9609	0.0499
TEMP	−80,334	27,711	−28,989	0.0037
RAINFALL	−354,464.6	202,600.2	−1.7495	0.0802
URBANPOP	−4.2186	1.5262	−2.7640	0.0057
C	4.3300	61,875	6.9899	0.0000
Method: Robust statistics				
R^2	0.5546	Adjusted R^2	0.5086	
Rw^2	0.8317	Adjusted Rw^2	0.8317	
Rn^2 statistic	145.0428	Prob (Rn^2)	0.0000	

Source: Author's estimate. Abbreviations: AGRINC: Agricultural income; C: Constant; DEFORATE: Deforestation; FCBI: Forest Carbon Benefit Indicator; FMCP: Forest management and conservation policies; Prob: Probability; RAINFALL: Rainfall vulnerability; TEMP: Extreme temperature; URBANPOP: Urban population.

The annual deforestation rate showed a positive coefficient, indicating that the FCBI increases with deforestation. Afforestation programs that accompany deforestation may temporarily sequester carbon, which explains this paradoxical result. Although cutting down mature forests may release carbon, afforestation or restoration effort scan introduce younger trees that absorb more carbon.[85] According to Robinson,[86] planting trees provides greater short-term advantages than long-term costs to biodiversity and the ecosystem; hence, deforestation should not be condoned. The forest sustainability index displayed a negative coefficient, suggesting an inverse relationship with the FCBI. Sustainable forest management practices, such as selective logging or reduced-impact logging, may initially lower overall carbon storage capability.[87] However, long-term sustainable forest management is crucial to preserving ecologically healthy forests that are more resilient to environmental pressures. This research emphasizes the need for a balanced forest management strategy that balances both short-term carbon sequestration and long-term sustainability.[88] The results demonstrated a strong negative relationship between temperature and FCBI. Forests are particularly vulnerable to climate change, as their carbon sequestration capacity declines with increasing temperatures.[89] Heat stress damages forest ecosystems, as Smigaj *et al.*[90] found. Elevated temperatures increase soil and plant respiration, releasing carbon into the atmosphere. Furthermore, extreme temperatures can reduce forest productivity and increase the risk of wildfires, further diminishing carbon stocks.[91] This research underscores the crucial need for adaptive forest management practices that improve forest resilience to heat stress in Pakistan, where temperatures have been rising due to climate change.

Rainfall has a negative coefficient, suggesting that excessive rainfall may hinder carbon sequestration. While precipitation is necessary for forest growth, excessive or irregular precipitation patterns can lead to soil erosion, waterlogging, and nutrient leaching, all of which harm forests. Sun *et al.*[92] stated that climate change-induced changes in precipitation patterns may disrupt the delicate balance of forest ecosystems. Climate variability is significantly altering Pakistan's rainfall patterns, adversely affecting forest ecosystems, and adaptation measures are needed to mitigate these effects. Another factor contributing to reduced carbon sequestration is human activity. Deforestation and carbon release often result from urbanization, infrastructure development, and agricultural conversion.[4] According to Qin *et al.*,[93] land-use change is a major driver of global carbon emissions. Pakistan's forest areas are under increasing pressure from urbanization and infrastructure growth. Deforestation not only degrades habitats and biodiversity but also reduces carbon sequestration.[94] Therefore, land-use planning and forest protection must be integrated to balance development with sustainability.

These findings have significant implications for Pakistan's climate change and carbon storage strategies. Deforestation, land-use changes, and agricultural activities contributed to nearly 200 million metric tons of carbon dioxide emissions in Pakistan in 2022. These emissions underscore the urgent need for focused efforts to mitigate carbon loss.[95] To prevent carbon sequestration from being hindered by agricultural growth, Pakistan could promote agroforestry, conservation tillage, and organic fertilizers. These approaches enhance soil health and increase carbon storage. Despite the benefits of afforestation in increasing carbon sequestration, long-term deforestation prevention remains critical. Expanding forest preserves, supporting community-based forest management, and curbing illegal logging are essential steps.[96] Adapting forests to changing rainfall patterns and rising temperatures is crucial. This may involve improving fire management practices, enhancing forest monitoring, and promoting the use of storm-resistant trees. Forest protection must be incorporated into sustainable land-use planning to reduce the impact of urbanization and infrastructure development on forest ecosystems.[97] Green infrastructure and park renovations could also contribute to carbon sequestration. Given that Pakistan is a signatory of the Paris Agreement, aggressive action is required to address climate change. Forest conservation efforts should align with broader climate and development goals, including renewable energy initiatives and sustainable waste management.[98]

5. Conclusion and policy recommendation

This study analyzed the factors influencing Pakistan's carbon storage capacity, including climate, precipitation, land-use changes, deforestation, agricultural income, and forest preservation regulations. The RLS regression analysis revealed that these factors significantly affect the FCBI. The study demonstrated that environmental processes and societal activities are interconnected, with agricultural dependence driving deforestation and land conversion, which in turn threatens forest carbon sequestration. Climate change exacerbated this situation by reducing Pakistan's forest carbon sequestration capacity through rising temperatures and altered precipitation patterns. In addition, urbanization and infrastructure development contributed to decreased carbon absorption by forests. The findings also indicate that reforestation may offer temporary improvements in carbon absorption, highlighting the complex relationship between deforestation and carbon sequestration. However, the unsustainability of this strategy emphasizes the urgent need for proactive forest protection. Pakistan faces substantial challenges from climate change, urbanization, and economic expansion. The loss of forest carbon capacity due to anthropogenic activities undermines both ecological stability and efforts to mitigate climate change. Therefore, achieving Pakistan's carbon sequestration and sustainable development goals requires a coordinated effort that balances social and economic growth with environmental preservation. The insights from this study on Pakistan's carbon sequestration dynamic scan guide more focused and effective governmental responses to these challenges.

The research recommends several policy actions aimed at reducing the human impact on Pakistan's forests and enhancing carbon sequestration. Policymakers should prioritize sustainable agricultural practices that do not compromise production for profit. Given the vital role of agriculture in the economy, it is crucial to promote farming techniques that support carbon sequestration. Initiatives like agroforestry, which involves growing crops alongside trees to enhance yields and store carbon, should be encouraged. Precision farming technologies can help reduce deforestation while increasing efficiency. Financial incentives should be provided to organic farmers to maintain soil carbon levels. These strategies require government subsidies, farmer education, and public awareness campaigns. Support for forest preservation initiatives is another key policy recommendation. As illegal logging and land conversion continue to threaten carbon sequestration, stronger regulations and enforcement are needed. Enhancing and expanding protected forests will help preserve biodiversity and carbon storage. Community-based forest management programs should be promoted, allowing local communities to participate in conservation and sustainable forest resource management. Policies should also encourage the replanting of native species to improve carbon absorption and maintain ecological stability. Furthermore, collaboration with international organizations and environmental agreements can provide additional financial and technical resources to strengthen conservation efforts.

Given that climate change is likely to further reduce forest carbon sequestration, adaptation and mitigation strategies are essential. Changes in precipitation and rising temperatures will continue to impact forest carbon storage. Climate-resilient forestry projects, such as improved forest management practices and the planting of drought-resistant trees, should be supported by the government. Studying these impacts will be key to mitigating the long-term effects of climate change on forest ecosystems. National development strategies must be aligned with climate change adaptation to ensure the health of both forests and economies. Communities must collaborate to mitigate the impacts of climate change on forests. As infrastructure development and urbanization continue to damage forest ecosystems, sustainable land-use planning becomes increasingly vital. Land-use changes hinder carbon sequestration, necessitating a comprehensive development policy that prioritizes forest conservation. Governments should incorporate forest preservation into zoning and urban development laws, providing incentives for businesses and developers to build sustainably and reduce land clearance. Furthermore, efforts to restore damaged through forestry and soil restoration initiatives should be encouraged, alongside robust monitoring systems to ensure efficacy and compliance with land-use regulations.

Finally, this research emphasizes the importance of global and regional cooperation in addressing climate change. Carbon trading mechanisms offer significant economic, technological, and scientific benefits to Pakistan. By participating in international carbon trading systems and partnering with environmental organizations, Pakistan can secure funding and expertise for forest conservation projects. Linking carbon sequestration goals with broader social and economic development objectives will help promote environmental sustainability. By adopting global environmental norms and seeking foreign financing, Pakistan can enhance its climate change mitigation efforts, strengthen its economy, and improve social well-being.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

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Availability of data

The data are freely available at World Development Indicators published by World Bank (2024) at https://databank.worldbank.org/source/world-development-indicators, and

CCKP (2024) at: https://climateknowledgeportal.worldbank.org/country/pakistan (accessed on 13th September, 2024).

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 67-82.
doi: 10.36922/ajwep.8163

ORIGINAL RESEARCH ARTICLE

Water quality assessment and health risk evaluation in Kushtia Municipality, Bangladesh: A comparative analysis of untreated water, treated water, and public water points

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Received: December 24, 2024; Revised: February 18, 2025; Accepted: February 19, 2025; Published Online: March 11, 2025

Abstract: Pipeline water supply, a primary source in urban areas, delivers treated water from water treatment plants (WTPs) directly to consumers. This study comprehensively evaluates water quality in Kushtia Municipality, Bangladesh, focusing on untreated water, treated water, and freely available public water point (PWP) samples. Twelve water samples were collected from March 1 to 7, 2024, and analyzed for physicochemical and microbiological parameters using standard methods. The treatment efficiency, water quality index (WQI), Nemerow pollution index (NPI), and hazard quotient were calculated based on the analytical measurements. Findings indicate that, among the 12 assessed parameters, only three comply with Bangladesh's water quality standards. The mean cumulative efficiency shows that WTP 2 exhibits the highest treatment efficiency (30.76%), whereas WTP 1 has the lowest (12.34%). While WQI scores classify all treated and PWP samples as "unfit" for consumption, treated water demonstrates comparatively better quality than PWPs. The NPI analysis identifies the primary contributing pollutants in the following order: Biochemical oxygen demand>hardness>alkalinity>iron>temperature>electrical conductivity. The health risk assessment reveals no significant risk of iron ingestion or dermal exposure for adults and children. However, long-term ingestion of arsenic-contaminated water presents a moderate health risk for both groups, while dermal contact poses no risk.

Keywords: Health risk assessment; Kushtia municipality; Nemerow pollution index; Physicochemical and microbiological parameters; Water quality index; Water treatment plants

1. Introduction

Safe and clean water is essential for human health and survival and is recognized as a fundamental human right.[1] Beyond sustaining life, water plays a critical role in socioeconomic development.[2] Water quality is often classified into three primary categories: biological, physical, and chemical, each characterized by distinct indicators. However, the pollution of these parameters has become a global concern, driven by population growth, agricultural and industrial activities, inadequate sewage management, and climate change.[3]

Water contamination, poor drinking water quality, and limited access expose populations to disease-causing organisms, pathogens, and hazardous levels of toxic substances and suspended solids.[4] These factors contribute to severe health issues, especially in low-income nations.[5] Poor drinking water quality is a primary source of waterborne diseases, including diarrhea, cholera, dysentery, and polio.[3,6] In addition, exposure to heavy metals in drinking water can lead to skin lesions, neurological disorders, gastrointestinal and renal dysfunction, and DNA damage, which may alter the cell cycle or contribute to cancer development.[7] Globally, unsafe water and poor sanitation affect billions of people, with 2 billion consuming fecal-contaminated water and 4.5 billion lacking proper sanitation.[6] These conditions account for over 80% of human illnesses, leading to approximately 2.2 million deaths annually in developing countries.[8] In Bangladesh alone, inadequate water, sanitation, and hygiene contribute to the deaths of around 400,000 children under 5 each year.[9] To mitigate health risks, drinking water must be free from pathogenic microorganisms and physicochemical pollutants.[3] Water treatment processes play a crucial role in removing impurities that could harm human health, and their efficiency directly determines drinking water safety.[10]

Despite government and non-governmental organization interventions, many water delivery systems remain insufficient, forcing communities to rely on unimproved water sources that pose serious health risks and reduce productivity.[11] In developing countries such as Bangladesh, pipeline-supplied water is rarely monitored, increasing the risk of service interruptions and contamination.[12] Previous studies found that 55.8% of municipalities in Bangladesh faced water quality issues, with contamination from iron (66.2%), leaks (13%), bacteria (11.7%), salinity (10.4%), arsenic (6.5%), manganese (5.2%), and odor (5.2%). Furthermore, waterborne diseases such as diarrhea (36.4%), dysentery (33.6%), and typhoid (17.1%) were prevalent.[13] Similarly, Molla *et al*.[14] reported that most water quality parameters in Chittagong, Bangladesh, exceeded safe drinking water limits. Given these challenges, extensive monitoring of drinking water treatment plants (WTPs) is required to ensure adequate water quality. However, fluctuations in water characteristics make water quality assessment expensive, labor-intensive, and complex.[15] Researchers continue to face issues in streamlining assessment methodologies while ensuring scientific accuracy and reliability.[16]

Drinking water quality has been evaluated using a range of assessment methodologies, such as treatment efficiency metrics, water quality index (WQI), Nemerow pollution index (NPI), and hazard quotient (HQ). Desye *et al*.[17] used percentage removal efficiency and WQI to evaluate the performance of a WTP from source to household in Gondar City, Northwest Ethiopia. Similarly, Hossain *et al*.[18] evaluated treatment efficiency and overall performance in Gopalganj, Bangladesh, using percentage removal efficiency and log removal value.

Other studies have investigated drinking water quality in various regions. Ahsan *et al*.[19] investigated drinking water quality in Dhaka City, Bangladesh, whereas Addisie[11] examined drinking water quality in the Ethiopian highlands. In central Sichuan Province, China, Su *et al*.[20] applied the NPI to identify the primary pollutants in drinking water from the Heilongtan Reservoir. Zakir *et al*.[21] investigated heavy metal-related health risks and calculated WQI scores in drinking water from Jamalpur Sadar, Bangladesh. Furthermore, Chakraborty *et al*.[22] estimated health risks and identified significant heavy metal contamination using the NPI in the rural region of Jashore, Bangladesh. These studies highlight the varied methodologies used to assess drinking water quality at regional and global levels and reveal significant gaps in drinking water quality assessment. While methods such as treatment efficiency metrics, WQI, the NPI, and health risk assessments have been widely applied, they are often used in isolation, limiting a comprehensive understanding of water quality dynamics. Comparative evaluations of these methodologies remain rare, leading to uncertainties regarding their relative effectiveness in different environmental and socioeconomic contexts. In addition, most studies fail to integrate microbial, chemical, and physical contaminants into a holistic risk assessment. Addressing these gaps is crucial for developing integrated, safe, and sustainable drinking water management frameworks.

Public water points (PWPs) serve as one of the primary drinking water sources for marginalized populations in Kushtia Municipality, Bangladesh. However, these sources are frequently neglected in water quality monitoring and associated health risk assessments. The physical, chemical, and microbial contaminants present in PWPs remain largely unknown, underscoring the need for a comprehensive investigation. To address this gap and improve public health outcomes for marginalized communities, this study aims to evaluate the efficiency of treatment plants, calculate the WQI for both treated and PWP water, identify key pollutants in the water supply network, and assess health risks associated with heavy metals in PWP water. This research contributes to scientific understanding by integrating multiple assessment methodologies while also offering practical insights for enhancing water safety and public health in Kushtia Municipality.

2. Materials and methods

2.1. Study area

Kushtia Municipality is the administrative center of Kushtia District, Khulna Division, Bangladesh. Its geographical coordinates are 23°54'10" N and 89°7'9" E. In 2011, the municipality (formerly referred to as the Old Municipality) comprised 12 wards; however, it has since expanded to 21 wards.[23] The municipality now spans 42.79 km^2 and has a population of 226,800.[24] Despite this growth, only four WTPs and overhead tanks have been installed in the area (Figure 1), primarily covering the area previously designated as the Old Municipality.

2.2. Hydrogeological and hydrographic framework

The hydrogeological framework of Kushtia Municipality consists of aquifers and aquitards, with groundwater-bearing zones identified through hydrostratigraphic analysis.[25] The municipality is situated adjacent to the Madhumati and Gorai Rivers, which significantly influence groundwater recharge and discharge processes. The region's subsurface geology is primarily composed of unconsolidated sediments, such as sand and clay, forming shallow and deep aquifers that serve as the municipality's primary groundwater sources. The depth of groundwater typically ranges from 1 to 3 m, indicating a high water table that is particularly susceptible to external contamination.[26] Groundwater recharge primarily occurs through precipitation infiltration and riverbank filtration, especially during the monsoon season, while groundwater discharge helps sustain river flow during dry periods.[27] However, the interaction between surface water and groundwater is dynamic and complex, posing potential contamination risks when surface water sources are polluted. Contaminants from industrial discharge, agricultural runoff, and untreated wastewater can infiltrate groundwater, leading to water quality degradation and associated public health hazards.[28]

2.3. Water treatment technologies and public water supply systems

The water treatment processes and technologies used in Kushtia Municipality align with those described by Fayshal *et al*.[29] The municipality operates four WTPs designed primarily for the removal of arsenic and iron. After treatment, the purified water is pumped into

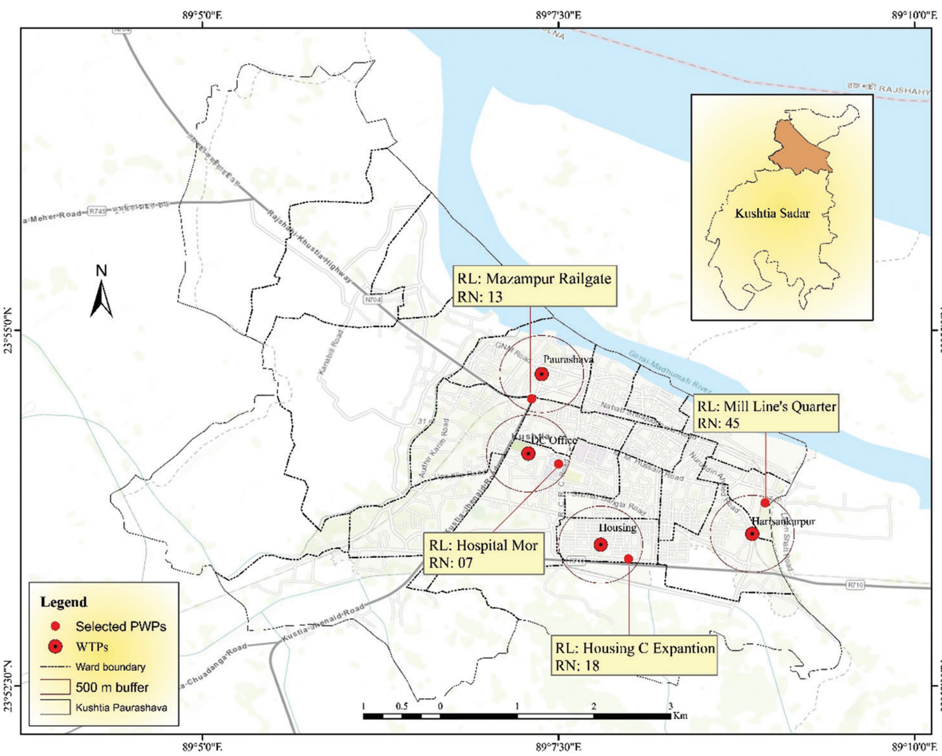

Figure 1. Study area and sampling points. The larger dots represent water treatment plants and overhead storage tanks, whereas the smaller dots indicate public water points.

overhead storage tanks, which serve as the primary distribution points for the municipality's pipeline network, broadly representing the overall water quality.

At present, Kushtia Municipality supplies water through two primary modes. The first mode includes 10,158 private pipeline connections, covering approximately 33% of the total municipal area.[24] The second mode consists of 56 PWPs, of which 39 are currently operational. These PWPs provide free access to drinking water, primarily serving marginalized communities. The locations of these PWPs are detailed in Table S1.

2.4. Sampling, sample collection, and analysis

Water samples were collected from Kushtia Municipality's four WTPs and key points within the municipal pipeline network to assess water quality trends across the distribution system. At each WTP, one sample was collected from the inlet (untreated water) and one from the outlet (treated water exiting the overhead storage tanks). In addition, four samples were purposively selected from a 500 m buffer zone based on consultations with local authorities, preliminary assessments, and geographic and usage considerations within the network. While the sample size was limited, the study aimed to capture general water quality trends across the distribution system, balancing practicality and cost-effectiveness with analytical feasibility.

In total, 12 water samples were collected from March 1 to March 7, 2024, covering different stages of treatment. The samples were categorized into three sources: (i) four untreated samples from WTP inlets, (ii) four treated samples from overhead storage tanks, and (iii) four samples from PWPs. The sampling locations are illustrated in Figure 1. Polypropylene plastic bottles were used for sample collection. Before sampling, bottles were thoroughly washed, rinsed with deionized water, autoclaved, and dried completely in a laminar flow hood. Dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), pH, temperature, and oxidation-reduction potential (ORP) were measured on-site, while all other parameters were measured in the laboratory. Samples were kept at 4°C until analysis.[30] The analytical instruments and methodologies used for sample analysis are summarized in Table 1.

2.5. Quality assurance (QA) and quality control (QC) procedures

Multiple QA/QC techniques were implemented to ensure measurement accuracy and reliability. Instruments were routinely calibrated using standard solutions to maintain precision. Blank tests were conducted to account for background interference, whereas control tests with known reference values ensured measurement consistency. Before use, reagents were tested for expiration dates and compliance with analytical requirements. To assess measurement repeatability and accuracy, triplicate measurements (n = 3) were conducted for each sample, and results were compared for consistency. Equipment was regularly maintained and inspected to prevent systematic errors. Calibration records, QA/QC documentation, and maintenance logs were systematically maintained to verify the performance and reliability of analytical techniques.

2.6. Treatment efficiency

The removal efficiency of a WTP is defined as the percentage reduction of a pollutant or a set of pollutants from influent (untreated) to effluent (treated) water.[31] A higher removal efficiency indicates that the WTP effectively removes contaminants and improves water quality. This study used Equations I – II to calculate individual treatment efficiency and mean cumulative efficiency for all measured parameters.[4] The individual efficiency (ef_{kt}) for the k-th water parameter at time t (at the time of analysis) was calculated using:

$$ef_{kt} = [1 - (C_{o,t})_k / (C_{in,t})_k] \times 100 \quad \text{(I)}$$

where C_o and C_{in} represent treated and untreated water, respectively.

The mean cumulated efficiency (MCE_t) for n water parameters at the time t was determined using:

$$MCE_t = \frac{1}{n}\sum_{j=1}^{n} ef_{jt} \quad \text{(II)}$$

2.7. WQI calculation

A total of 13 parameters (Table S2) were utilized to determine the WQI using the weighted average method, initially developed by Horton[32] and later refined by Brown *et al*.[33] The mathematical calculation of WQI was carried out in three stages: (i) determining the unit weight (*Wn)* of water quality parameters, (ii) calculating the subindex or quality rating of the water quality parameters, and (iii) aggregating these values to obtain the final WQI.

2.7.1. Calculation of Wn

The *Wn* of each water quality parameter was calculated using Equation III, which divides the constant of

Table 1. Analytical parameters and methods for laboratory testing

Parameters	Analyzer	Model and brand	Analytical method	Standard values	References
Alkalinity	Test kit (LR and HR)	LH2018 and LH2019 (Lohand)	Acid-base titration method	20 – 200	64
Hardness	Test kit	LH2013 (Lohand)	EDTA titration method	80 – 100	
Chloride	Test kit	LH2015 (Lohand)	Silver nitrate titration method	150 – 600	
DO	DO meter (Acc. ±0.4)	DO-5509 (Lutron)	Electrochemical reaction	6	
BOD_5	BOD meter	BOD-PC02 (BIOBASE)	Respirometric (Incubation)	0.2	
COD	COD meter (Acc. ±5%)	LH-C3 (Lohand)	Rapid digestion spectrophotometry	4	
Iron	Iron checker (Acc. ±0.04)	HI-721 (Hanna)	Colorimetric	0.3 – 1.0	
Arsenic	Test kit (LR)	Test Strip (Hach)	Colorimetric	0.05	
TDS	Multimeter (Acc.±1%)	CON30 (CLEAN)	Electrochemical reaction	1,000	
EC	Multimeter (Acc.±1%)	CON30 (CLEAN)	Electrochemical reaction	700	
pH	Multimeter (Acc.±0.01)	PH-220 (BIOBASE)	Electrochemical reaction	6.5 – 8.5	
Temperature	Multimeter (Acc.±0.5°C)	PH-220 (BIOBASE)	Electrochemical reaction	20 – 30	
ORP	Multimeter (Acc.±1 mV)	PH-220 (BIOBASE)	Electrochemical reaction	650 – 700	65
Bacterial load (CFUs)	Plate count agar	M091A-500G (HiMedia)	Plate count method (48 h at 37°C)	-	-

Abbreviations: BOD_5: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; EDTA: Ethylenediaminetetraacetic acid; HR: High range; LR: Low range; ORP: Oxidation-reduction potential; TDS: Total dissolved solids.

proportionality (k) by the standard acceptable value (Sn) of a given parameter:

$$W_n = k / Sn \tag{III}$$

k was determined using Equation IV:

$$k = 1 / (\sum \frac{1}{S_n}) \tag{IV}$$

(ii) Calculation of subindex or quality rating

The subindex (q_n) for each water quality parameter was calculated using Equation V:

$$q_n = \frac{V_n - V_{id}}{S_n - V_{id}} \times 100 \tag{V}$$

where V_n is the observed value of the n-th water quality parameter, and V_{id} is the ideal value for the n-th parameter. For pH, $V_{id} = 7$, for DO, $V_{id} = 14.6$ mg/L, and for all other parameters, V_{id} is usually zero [[34]. The calculated $1/Sn$, k, and W_i are represented in Table S2.

(iii) Calculation of aggregated WQI

The aggregated WQI was calculated using Equation VI:

$$WQI = q_n W_n / W_n \tag{VI}$$

The WQI values were classified into the following categories for drinking water quality assessment[34]: Excellent (0 – 25), good (26 – 50), bad (51 – 75), very poor (76 – 100), and unsuitable for drinking (>100).

2.8. Pollution index

This study used NPI to identify the primary pollutants in the water supply network. The NPI provides a comprehensive evaluation of water quality by prioritizing the most pollutants while accounting for the influence of other contributing factors in the assessment system.[20] A parameter is considered non-polluting when the NPI value is ≤1.[35] The NPI was computed using Equation VII:

$$NPI = \sqrt{\frac{(P_1)^2 + (P_{imax})^2}{2}} \quad \text{(VII)}$$

where the single factor index (P_I) represents the average value of the single-factor pollution index, and P_{imax} represents the maximal single-item pollution index among the pollutants at a given sampling point. P_I was calculated using Equation VIII:

$$P_1 = \frac{C_1}{S_i} \quad \text{(VIII)}$$

where C_i is the measured concentration of the targeted pollutant, and S_i is the standard permissible limit of that parameter.

2.9. Estimation of non-carcinogenic human health risks

2.9.1. Chronic daily intake (CDI)

The United States Environmental Protection Agency defines a human health risk assessment as "the process of estimating the nature and probability of adverse health effects in humans who may be exposed to chemicals in contaminated environmental media, now or in the future."[36] In this study, iron and arsenic were used to determine the non-carcinogenic health hazards associated with direct consumption and dermal absorption from pipeline-supplied water samples. The CDI was calculated using Equations IX and X[37]:

$$CDI_{Ingestion} = \frac{C_w \times IR \times EF \times ED}{BW \times AT} \quad \text{(IX)}$$

$$CDI_{Dermal} = \frac{C_w \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT} \quad \text{(X)}$$

where $CDI_{ingestion/dermal}$ is expressed in µg/kg/day; C_w is the measured concentration of the contaminant in water (µg/L); *IR* is the ingestion rate; *EF* denotes the exposure frequency (day/years); *ED* is the exposure duration (year); *BW* is the average body weight (kg); *AT* refers to the average time (day); *SA* is exposed skin-surface area (cm²); *ET* is the exposure time (h/event); *CF* is conversion factor (L/cm³); and K_p is permeability coefficient (cm/h). Table 2 presents the input assumptions and values used to calculate CDI for ingestion and dermal absorption in adults and children.

2.9.2. HQ

The HQ is the ratio of CDI to the reference dose (RfD) for a given contaminant,[38] expressed as follows (Equation XI):

$$HQ_{ingestion/dermal} = \frac{CDI}{RfD} \quad \text{(XI)}$$

where *RfD* represents the RfD for the corresponding heavy metals. The RfD for iron is 700 µg/kg/day,[37] and arsenic is 0.3 µg/kg/day.[39] The HQ values were categorized as follows: (i) negligible risk (HQ < 0.1); (ii) low risk, (0.1 < HQ < 1.0); (iii) moderate risk (1.0 < HQ < 4.0), and (iv) high risk (HQ > 4.0).[40]

Table 2. Parameters, input assumptions, and values for chronic daily intake calculation via dermal absorption and ingestion for adults and children

Parameter	Ingestion		Dermal absorption		References
	Adult	Children	Adult	Children	
Measured metal concentrations (µg/L)	-	-	-	-	-
Ingestion rate (L/day)	3.5	1.32	-	-	37,38,66
Dermal permeability coefficient (cm/h)	Iron: 1×10⁻³, Arsenic: 4×10⁻⁴		-	-	
Exposure time (h/event)	0.58	1	-	-	
Skin-surface area (cm²)	18,000	6,600	-	-	
Exposure duration (year)	30	6	30	6	
Exposure frequency (day/years)	365				
Conversion factor (L/cm³)	0.001		-	-	
Body weight (kg)	57.5	15	57.5	15	
Average time (day)	10,950	2,190	10,950	2,190	

3. Results

3.1. Drinking water quality assessments

The comparative analysis of water quality parameters reveals significant deviations from standard values across untreated, treated, and PWP samples (Figure 2). Alkalinity and hardness levels consistently exceed the permissible limits of 200 mg/L and 100 mg/L, respectively. Chloride levels remain within the safe limit of 600 mg/L. However, DO levels in untreated and PWP samples are critically low (2.0 – 3.8 mg/L) compared to the standard of 6 mg/L, and the treatment process only

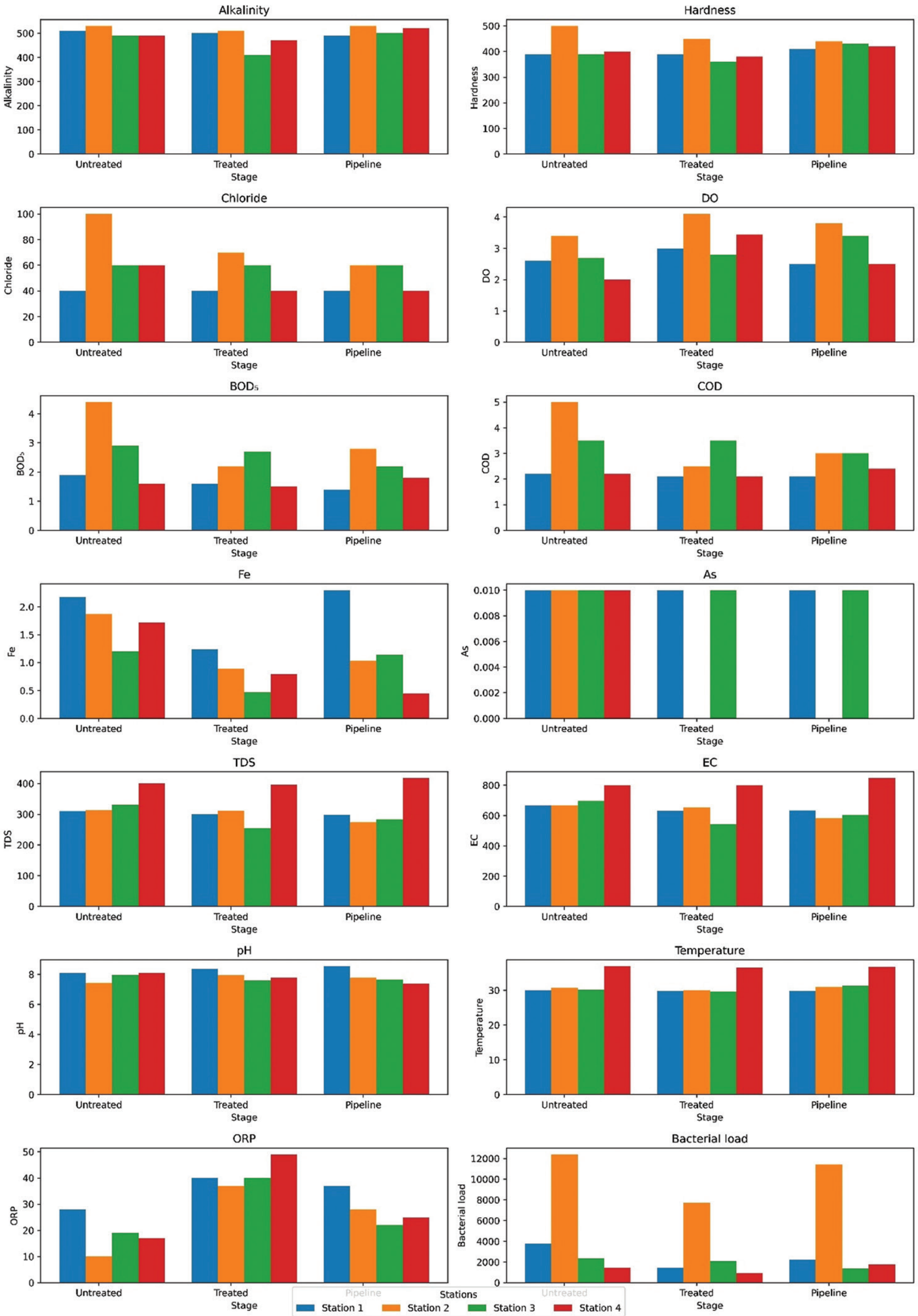

Figure 2. Measured water quality and comparisons

Abbreviations: As: Arsenic; BOD_5: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; Fe: Iron; ORP: Oxidation-reduction potential; PWP: Public water point; TDS: Total dissolved solids.

marginally improves DO levels. Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) are also elevated in untreated water, with residual levels in treated and PWP samples exceeding the standards of 0.2 mg/L and 4 mg/L, respectively.

Iron levels in untreated samples (1.20 – 2.18 mg/L) exceed the permissible limits of 1 mg/L but are substantially reduced in treated water. Arsenic concentrations remain within permissible limits (0.05 mg/L) across all samples. TDS and EC values fall within acceptable limits of 1,000 mg/L and 700 μS/cm, respectively. pH levels are slightly alkaline but fall within permissible ranges, while temperature levels exceed the standard of 30°C, particularly in untreated samples, which may affect microbial activity and treatment efficiency. ORP values are notably below the standard (700 mV). Microbiological analysis reveals alarmingly high bacterial loads (1,425 – 12,395 CFUs). Although treatment considerably reduces bacterial counts, PWP water frequently exhibits recontamination, especially in Samples 2 and 4.

Overall, treated water samples demonstrate notable improvements in bacterial load, iron concentration, and organic pollutants (BOD_5 and COD) compared to untreated and PWP samples. Among the treated samples, Sample 4 in treated samples exhibits the best overall performance, with the lowest bacterial load (900 CFUs) and reduced parameter levels approaching standard values. However, alkalinity and hardness remain elevated beyond permissible limits. In contrast, untreated samples, particularly Sample 2, exhibit the poorest water quality, characterized by alarmingly high bacterial loads (12,395 CFUs), elevated BOD_5 (4.4 mg/L) and COD (5.0 mg/L), and excessive hardness (500 mg/L), indicating severe contamination and extremely poor water quality. PWP samples demonstrate intermediate water quality, but the recontamination observed in Sample 2 and Sample 4 renders them less reliable for consumption compared to treated water.

3.2. Treatment efficiency of the WTPs

The analysis of water treatment performance across four WTPs indicates variability in removal efficiency for different parameters (Figure 3). WTPs 2 and 4 demonstrate high effectiveness in arsenic removal, whereas WTP 3 exhibits the highest iron removal efficiency (60.83%) and is also the most effective in reducing TDS (23.26%) and EC (21.98%). Beyond arsenic removal, WTP 2 is highly effective at reducing BOD_5 (50%), COD (50%), and chloride (30%). DO levels increased across all WTPs, with WTP 4 exhibiting the most significant improvement (72.5%). ORP values also increase considerably across all WTPs, with WTP 2 recording the highest increase (270%). Among the treatment facilities, WTP 1 achieves the highest bacterial load reduction (61.59%). The MCE_t results

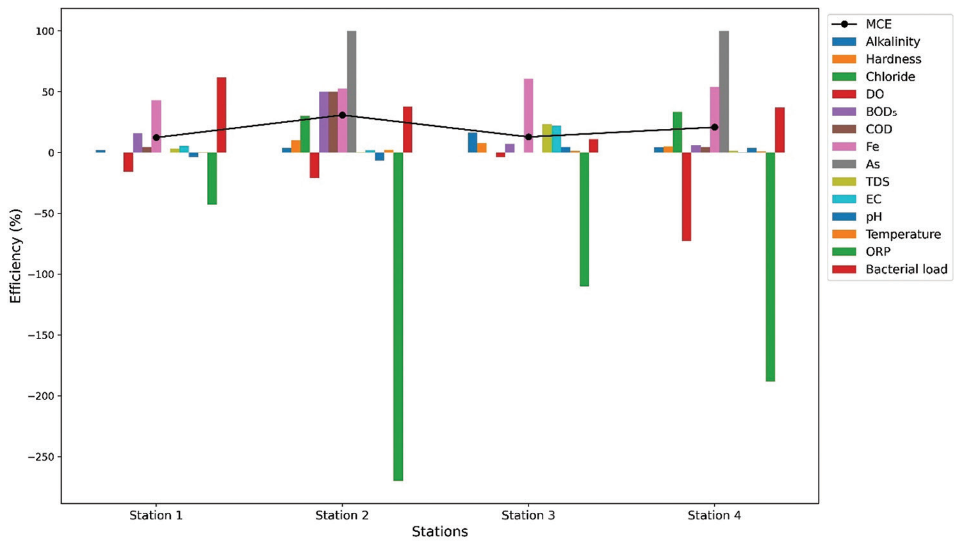

Figure 3. Removal efficiency of the WTPs

Abbreviations: As: Arsenic; BOD_5: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; Fe: Iron; MCE: Mean cumulated efficiency; ORP: Oxidation-reduction potential; PWP: Public water point; TDS: Total dissolved solids.

indicate WTP 2 (30.76%) exhibits the highest overall treatment efficiency, followed by WTP 4 (20.85%), WTP 3 (12.81%), and WTP 1 (12.34%). These findings demonstrate variability in total water treatment efficacy across different WTPs.

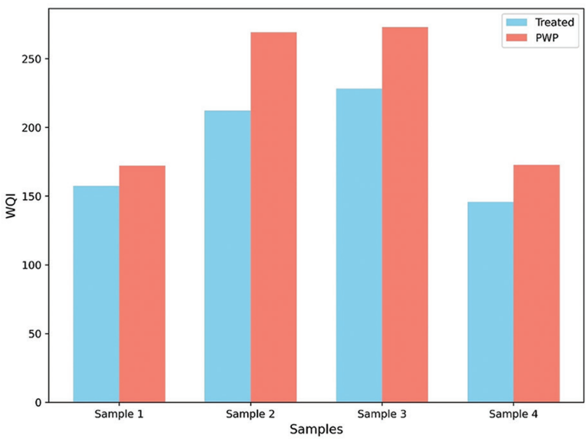

Figure 4. WQI across different samples

Abbreviations: PWP: Public water point; WQI: Water quality index.

3.3. WQI for the selected stations

The WQI values (Figure 4) highlight serious water quality concerns, as all samples are classified as "unfit" for consumption. Furthermore, WQI values for PWP samples are consistently higher than for treated samples across all four WTPs. Among the tested samples, Sample 3 exhibits the highest WQI values, with the PWP sample demonstrating significantly worse quality than the treated sample. In contrast, Sample 4 records the lowest WQI values for both treated and PWP samples.

3.4. Correlation analysis of water quality parameters and the WQI

The correlation analysis uncovers several noteworthy relationships among water quality parameters (Figure 5). A correlation coefficient of 0.97 between BOD_5 and COD suggests a significant positive relationship, indicating that higher BOD_5 values are strongly linked to increased COD values. Both BOD_5 and COD serve as key indicators of organic contamination in water. Similarly, a correlation coefficient of 0.98 between EC and TDS confirms a strong relationship, as EC

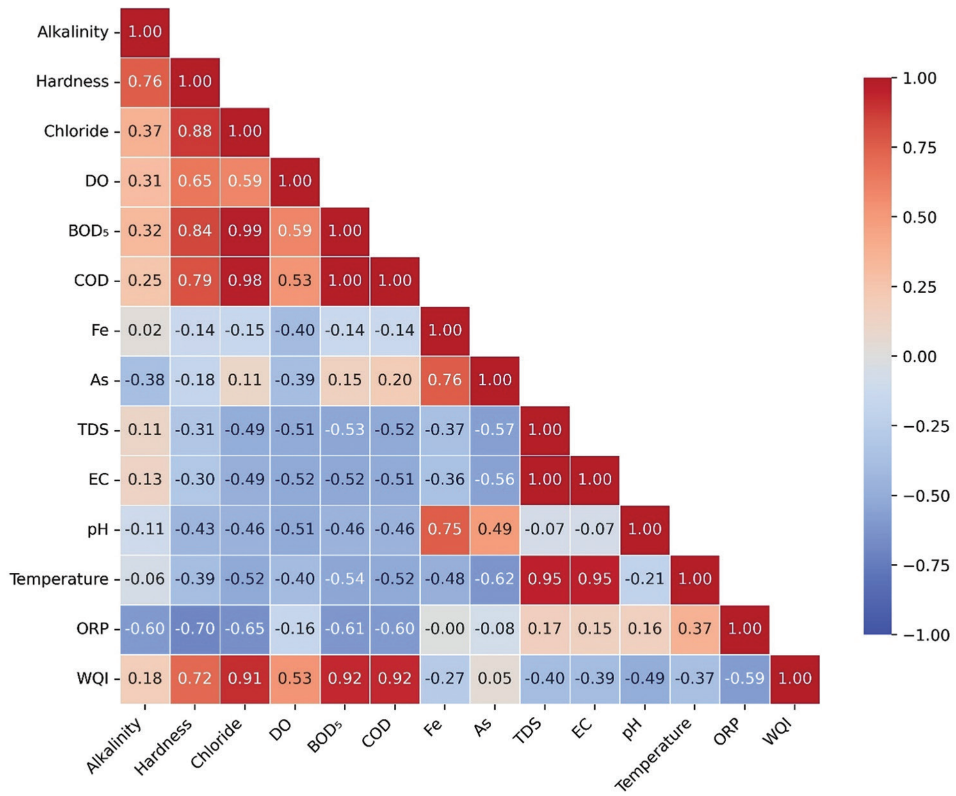

Figure 5. Correlation between physicochemical and biological parameters and PWP's WQI

Abbreviations: As: Arsenic; BOD_5: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; Fe: Iron; ORP: Oxidation-reduction potential; PWP: Public water point; TDS: Total dissolved solids; WQI: Water quality index.

is frequently used as a proxy for measuring TDS concentrations. A significant positive connection (0.87) between EC and temperature indicates that higher temperatures are linked to greater EC values. Furthermore, robust positive associations exist between WQI and key indices such as BOD_5, COD, chloride, and hardness, emphasizing their substantial influence on overall water quality. A moderate positive correlation (0.73) between chloride and hardness further supports the interdependence of these parameters. Moreover, a correlation coefficient of 0.58 between iron and arsenic implies that regions with elevated iron levels are also likely to exhibit elevated arsenic levels, indicating a shared geochemical origin for both pollutants.

Conversely, several notable negative associations are identified. ORP negatively correlates with alkalinity, hardness, chloride, BOD_5, and COD. In addition, a negative correlation between pH and chloride was observed.

3.5. Identification of the key polluting factors

Figure 6 illustrates significant variations in the NPI across the sampled stations, emphasizing eight key factors contributing to drinking water pollution: alkalinity, hardness, chloride, BOD_5, COD, iron, EC, pH, and temperature. The highest NPI values among these parameters are recorded for alkalinity (5.91), hardness (6.81), BOD_5 (26.99), COD (1.52), iron (2.98), EC (1.32), pH (1.4), and temperature (1.73). According to the overall NPI rankings, six parameters emerge as the primary contributors to drinking water pollution in the study area. The dominant pollutants, listed in order of impact, are: BOD_5>hardness>alkalinity>iron>temperature>EC. This comprehensive assessment identifies the key pollutants influencing water quality and underscores the need for targeted water treatment and management measures.

3.6. Health risk analysis

Table 3 presents the CDI values for iron and arsenic across the four samples in PWPs. The CDI for iron is consistently higher than that for arsenic. For ingestion, the CDI of iron and arsenic ranges from 27.39 – 140 μg/kg/day to 0 – 0.6086 μg/kg/day for adults and from 39.6 – 202.4 μg/kg/day to 0 – 0.88 μg/kg/day for children, respectively. For dermal exposure, the CDI of iron and arsenic ranges from 0.0817 – 0.418 μg/kg/day to 0 – 0.00073 μg/kg/day for adults and 0.198 – 1.012 μg/kg/day and 0 – 0.00618 μg/kg/day for children, respectively. Comparatively, Sample 4 exhibits the lowest CDI values, whereas Sample 1 records the highest.

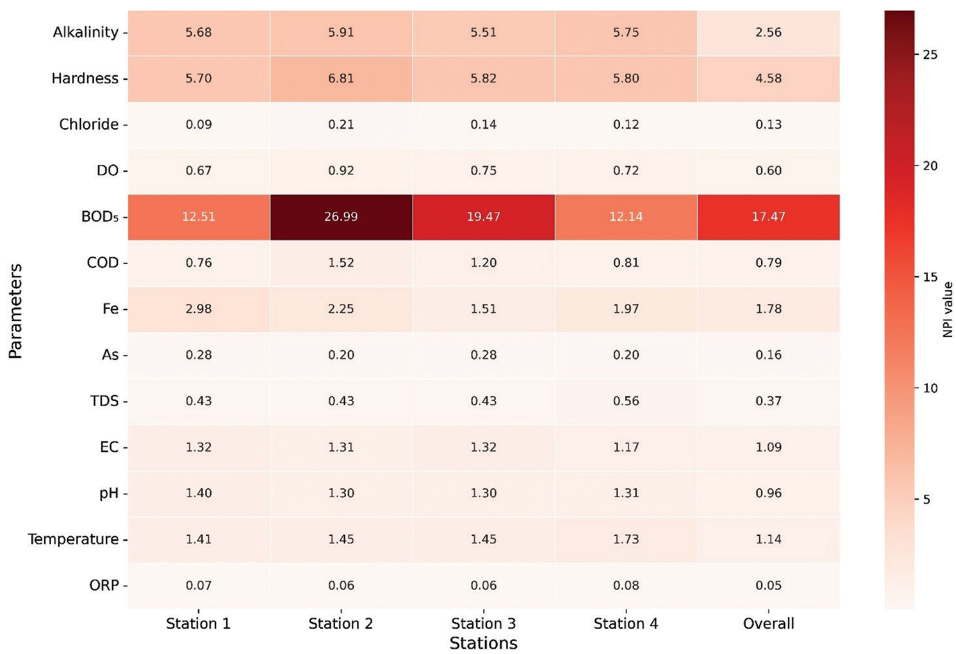

Figure 6. Heatmap representing NPI scores for all samples, with scores above 1 indicating water-polluting factors

Abbreviations: As: Arsenic; BOD_5: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; Fe: Iron; NPI: Nemerow pollution index; ORP: Oxidation-reduction potential; TDS: Total dissolved solids.

Table 4 presents the HQ of iron and arsenic across the same sampling stations, highlighting variability in potential health hazards for adults and children. HQ values for iron remain below 1.0 for both ingestion and dermal contact, indicating minimal health risk. However, HQ values are comparatively higher in children than in adults, suggesting increased susceptibility. In contrast, the HQ values for arsenic reveal a concerning trend. Samples 1 and 3 exhibit HQ values of 2.03 and 2.93, respectively, for both adults and children due to ingestion, placing them in the moderate risk category. These findings indicate a potential health concern for both groups. Conversely, arsenic levels in Samples 2 and 4 are undetectable (HQ = 0), indicating no associated health risk. In addition, no risk was observed for dermal exposure to arsenic at any sampling station. Overall, the findings indicate that while iron levels pose minimal health risks across all stations, arsenic contamination in certain stations presents a considerable health hazard, particularly for children. These findings underscore the necessity for targeted interventions to mitigate arsenic exposure and reduce potential health risks in affected areas.

4. Discussion

This study examines the physicochemical and biological properties of drinking water across four sampling stations. While high alkalinity and hardness levels exceeding permissible limits do not necessarily pose direct health risks, excessive levels can have laxative effects.[41] Moderately alkaline water can prevent metal pipe corrosion, whereas high alkalinity and hardness can adversely affect plumbing systems.[42] A strong positive relationship was observed between alkalinity and hardness, with hardness exerting a moderate impact on the WQI and contributing more significantly to water pollution. Although chloride levels remain within safe limits, excessive amounts can impart an unpleasant salty taste.[43] Low DO values suggest potential oxygen depletion, which can accelerate unpleasantness to some people[43] and also lead to the corrosion of metal pipes and plumbing fixtures.[44] The elevated BOD_5 across all samples indicates severe organic contamination, suggesting the presence of pathogenic microbes capable of causing waterborne illnesses.[45] As the concentration of organic material increases in the water, bacterial metabolism results in greater oxygen consumption, raising BOD_5 levels.[43] Similarly, high COD levels indicate the presence of diverse organic pollutants, contributing to waterway contamination and further reducing DO levels.[46] Iron concentrations exceeding permissible levels can result in iron overload, causing symptoms such as stomach upset, constipation, nausea, abdominal pain, vomiting, and diarrhea.[47] In addition, iron compounds in water may irritate the skin and produce oxidative stress, resulting in the production of highly reactive oxygen radicals that damage cell membranes and proteins, ultimately compromising

Table 3. Chronic daily intake values for iron and arsenic across different public water point samples

Sample	Iron (µg/kg/day)				Arsenic (µg/kg/day)			
	Ingestion		Dermal absorption		Ingestion		Dermal absorption	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Sample 1	140	202.4	0.4175995	1.012	0.6086	0.88	0.00073	0.00176
Sample 2	62.69	90.64	0.18701195	0.4532	0	0	0	0
Sample 3	69.38	100.32	0.2069841	0.5016	0.6086	0.88	0.00073	0.00176
Sample 4	27.39	39.6	0.08170425	0.198	0	0	0	0

Table 4. Calculated hazard quotient values for treated and public water point water samples

Sample	Iron				Arsenic			
	Ingestion		Dermal absorption		Ingestion		Dermal absorption	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Sample 1	0.2	0.29	0.0006	0.001	2.03	2.93	0.002	0.006
Sample 2	0.09	0.13	0.0003	0.0006	0	0	0	0
Sample 3	0.1	0.143	0.0003	0.0007	2.03	2.93	0.002	0.006
Sample 4	0.04	0.06	0.0001	0.0003	0	0	0	0

skin health.[48] The high iron levels observed in multiple samples may thereby pose potential health hazards. Elevated EC levels indicate the presence of dissolved contaminants, including salts, alkalis, chlorides, sulfides, and carbonates, which degrade water quality.[49] While high pH can cause water to develop a bitter taste, low pH values increase the solubility of toxic heavy metals such as cadmium, lead, and chromium.[50] The low arsenic level detected in this study may be attributed to the near-neutral pH conditions.[49]

The ORP levels fall below the permissible range, indicating low DO levels. Higher ORP values are associated with increased DO levels, whereas low ORP levels indicate microbial contamination.[51] Temperature is a critical determinant of water quality, influencing both physical and chemical characteristics. It affects metabolic rates, photosynthetic activity, chemical toxicity, DO concentrations, conductivity, salinity, ORP, pH, and water density. In addition, temperature variations impact sedimentation, chlorination efficiency, and BOD_5 dynamics.[52,53] Elevated bacterial loads in drinking water increase the risk of coliform bacteria, particularly *Escherichia coli*, which can cause severe health issues. Infants, the elderly, and immunocompromised individuals are especially vulnerable to these pathogens.[54] Although treatment processes improve water quality, certain parameters – such as DO, pH, ORP, and bacterial load – often deteriorate post-treatment, indicating inefficiencies in water management and potential failures in the distribution system.[55]

The WQI of PWPs is significantly lower than that of treated water, as shown in Figure 4. This decline suggests deteriorating water quality at PWPs, necessitating further investigation to determine the causes and key influencing factors. Previous studies indicate that several interrelated factors, including microbial growth, contamination events, and physical changes in distribution networks, contribute to the degradation of pipeline-supplied water quality. Biofilms, which consist of microbial communities adhering to pipe walls, play a crucial role in water quality deterioration by increasing disinfectant demand and serving as reservoirs for pathogens, thereby posing serious health risks.[56] It is estimated that up to 95% of the total microbial biomass in water distribution systems resides within biofilms, which alter water characteristics as the water travels through pipelines.[56] Furthermore, the age and material composition of pipeline infrastructure, combined with challenges associated with urbanization, significantly impact water quality decline. Aging and outdated piping systems may permit the intrusion of contaminants, leading to increased turbidity levels and potential health risks.[57]

The NPI identifies BOD_5, hardness, alkalinity, temperature, and EC as the primary contributors to water pollution. Furthermore, the correlation matrix reveals strong associations between BOD_5, COD, chloride, and hardness with the WQI of PWP samples (Figure 5). These parameters are the principal factors rendering water unsuitable for consumption across all samples (Figure 6). A similar pattern was observed in Old Dhaka, where 100% of surveyed respondents reported that municipal water was unsafe for drinking.[58] This highlights the urgent need to manage these parameters to improve drinking water quality. To solve this problem, various mitigation measures can be implemented, including identifying pollution sources, using advanced treatment technologies such as membrane filtration, reverse osmosis, and other advanced methods, and implementing routine monitoring, maintenance, and pipeline replacement strategies, including detecting leaks, addressing corrosion, and mitigating other infrastructure-related issues.[59]

The health risk assessment indicates no carcinogenic risk from iron for adults or children through ingestion or dermal contact despite some samples exceeding standard levels. However, excessive iron concentrations adversely affect municipal applications, industrial machinery, and agricultural productivity.[60] While all samples comply with the permissible standard for arsenic, the HQ values suggest that long-term ingestion of arsenic-contaminated water poses a moderate risk for both adults and children. Chronic exposure to arsenic-contaminated water is a significant public health issue in Bangladesh, as it leads to arsenic poisoning and severe health complications.[61] To mitigate these risks, advanced water treatment technologies, such as electrocoagulation, reverse osmosis, and nanofiltration, have demonstrated effectiveness in reducing arsenic and iron levels in drinking water.[62,63] The adoption of these technologies, coupled with a public awareness campaign, can significantly reduce long-term health risks associated with heavy metal contamination.

5. Conclusion

This study provides critical insights into drinking water quality in Kushtia Municipality, Bangladesh, highlighting significant concerns regarding WTP performance, overall water quality, and associated public health risks. The findings reveal that multiple physicochemical and biological parameters frequently exceed permissible limits, contributing to water pollution and rendering PWP water unsuitable for consumption. The WQI analysis indicates a substantial decline in water quality from WTPs to PWPs, with key parameters such as BOD_5, hardness, alkalinity, iron, temperature, and EC exceeding safe drinking water standards. High BOD_5 and COD levels suggest severe organic contamination, potentially harboring pathogenic microbes. The regression analysis identifies a slight increase in WQI with distance, implying that factors beyond distribution distance, such as microbial growth, pipe conditions, and biofilm formation, contribute to water quality deterioration within the supply network. In addition, the pollution index confirms that BOD_5, hardness, alkalinity, temperature, and EC are the primary contributors to water pollution. The health risk assessment indicates that iron contamination poses minimal health concerns, while arsenic remains a significant threat, particularly for children. Long-term exposure to arsenic-contaminated water is associated with severe health conditions despite arsenic levels generally complying with standard limits. However, HQ values highlight potential chronic health risks, warranting continued monitoring and intervention.

The deterioration of water quality along the distribution system points to ineffective management, aging infrastructure, and biofilm accumulation, all of which degrade water quality over time. In addition, PWPs, predominantly serving marginalized communities, are disproportionately affected by contamination, increasing vulnerability to waterborne diseases.

Addressing these issues requires the implementation of advanced treatment technologies, such as reverse osmosis, membrane filtration, and electrocoagulation, to improve contaminant removal efficiency. Strengthening routine water quality monitoring, enforcing strict regulatory compliance, and upgrading pipeline infrastructure are essential measures to mitigate contamination risks and ensure safe drinking water access. In addition, public awareness campaigns should be conducted to educate communities on water safety practices and proper storage methods. Policymakers must allocate resources to support sustainable water management strategies, including real-time monitoring systems and the expansion of safe water access for marginalized populations.

Future research should explore seasonal variations in water quality, pathogenic bacterial diversity, and community perceptions to develop a comprehensive water quality management framework. Implementing these measures will significantly enhance drinking water safety and public health in Kushtia Municipality, ensuring long-term sustainability and an improved quality of life for its residents.

Acknowledgments

The authors would like to acknowledge the Environmental Analysis Lab, Department of Geography and Environment, and Agricultural and Environmental Laboratory, Department of Biotechnology and Genetic Engineering, Islamic University, Kushtia, Bangladesh, for the instrumental facility.

Funding

None.

Conflict of interest

The authors declare there is no conflict.

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Availability of data

All relevant data are included in the paper.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 83-98.
doi: 10.36922/ajwep.7089

ORIGINAL RESEARCH ARTICLE

Examining how corporate environmental strategies influence the management of plastic pollution in food and beverage firms

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Received: December 6, 2024; Revised: February 26, 2025; Accepted: March 3, 2025; Published Online: March 14, 2025

Abstract: This research work aims to investigate how the corporate environmental strategy (CES) influences the management of plastic pollution. The focus of this study was a food and beverage (F&B) manufacturing firm in Durban, South Africa, because of their use of plastic items for packaging their products. Furthermore, when their product has served its function, it is disposed of, polluting the environment. There is a global worry as plastic waste is contaminating the land and marine environment. The pressure from different stakeholders for the accountability of those responsible has grown rapidly over the years. Quantitative information was gathered using a structured questionnaire to survey 128 F&B manufacturing companies' managers in finance, management, factory, and accounting departments. The data were analyzed with Statistical Package for the Social Sciences, and the Pearson correlation coefficient and regression analysis were used to examine the relationship between the variables. The findings revealed a positive relationship between CES and plastic pollution control (PPC). The R^2 value of 0.149 was obtained from the linear regression analysis, suggesting that CES accounts for 14.9% of the variance in PPC. Thus, a significant linear relationship between the two variables was discovered.

Keywords: Environmental degradation; Environmental management accounting; Plastic waste; Plastic recycling

1. Introduction

Several decades ago, industrial practitioners, environmental policymakers, academics, and businesses paid little attention to the environment because they believed that the products produced by their corporations had minimal environmental influence. Environmental degradation has become a global environmental issue.[1] While companies have sought to implement environmental management practices, which include methodologies, policies, and procedures to monitor and regulate the impact of their activities on the natural environment, they have been accused of greenwashing.[2] Firms are under a lot of pressure from stakeholders to lessen the environmental effects of their industrial activities. Businesses must prioritize environmental and nature conservation operations in light of the various environmental challenges that have been identified.[3,4] As firms attempt to adopt sustainable business strategies in the face of changing stakeholder demands, businesses, particularly manufacturers, are beginning to confront legal and societal demands to implement sustainable procedures and produce environmentally friendly products.

According to recent research focusing on environmental, social, and corporate governance, companies are searching for diverse corporate environmental strategies (CESs) that contribute significantly to the reduction of their environmental impact.[5] To achieve outstanding ecological performance, organizational assets must be utilized, including a pledge from senior executives, an initiative to implement corporate strategy with environmental challenges, and the use of environmental management accounting (EMA).[6] A sustainable firm frequently relies on senior management's dedication, which can eventually result in increased competitive advantage.[6,7] Existing research on this topic falls into two groups. Some researchers argue that using green industrial methods to save money and enhance efficiency may result in bottlenecks. Long-term investments in lowering hazardous emissions may outweigh the economic advantages of the companies. On the contrary, other research suggests that organizations with a strong desire to create environmental policies are more likely to achieve excellent economic performance. Most experts feel that implementing CESs improves both social and environmental performance.[8]

In the past decade, corporate researchers and practitioners have been primarily motivated by "green" concerns.[9] Numerous studies have been conducted on CESs around the globe[10-13] and it was noted that most scholars in the early 2000s explored it as an avenue to sustainability and sustainable development. Based on the studied literature, it was discovered that studies on CES and plastic pollution mitigation throughout the world remain scarce. However, plastics have contributed to a surge in plastic pollution, and a slew of severe environmental issues, and any mishandling of plastic waste endangers both the environment and the well-being of people in many developing nations.[14] Despite increased attention to plastic pollution over the last decade, research indicates that the problem is worsening. The epidemic has caused a significant setback in attempts to reduce the quantity of plastic generated and its frequency of usage. Despite the broad increase in restrictions and/or tax-based incentives to reduce use, it has reenergized the single-use plastic (SUP) industry. Even before the pandemic, there was a need for a significant change in the global production-consumption-waste cycle.[15]

The continuous growth of plastic pollution is an environmental hazard that necessitates the adoption of alternative sustainable measures. The aim of this article is to investigate how CES influences plastic pollution control (PPC) in food and beverage (F&B) manufacturing companies in Durban, South Africa. Specifically, it examines whether incorporating environmental strategies in these manufacturing firms can enhance plastic pollution management. According to Arijeniwa *et al.*,[16] the growing problem of plastic pollution needs prompt action, notably from the F&B business, which contributes significantly to SUP waste. Therefore, F&B manufacturers may need to start implementing plastic pollution reduction measures inside their operations and incorporate them into their organizational structure and company policies. This study was conducted to bridge that gap in the literature and to gain the attention of companies, government officials, and policymakers who are interested in sustainable practices.

2. Previous literature and hypothesis development

2.1. Environmental management in business: A review of literature, current practices, and emerging challenges

The reduction of ecological harm arising from company operations and the preservation of the environment as a whole are indicators of a firm's environmental sustainability and have gained more scrutiny from the world, requiring firms to mitigate their detrimental effects on the environment and contribute to sustainable development.[17] Environmental sustainability refers to a variety of actions and regulations designed to reduce a company's influence on the natural environment. These practices include reducing energy and waste, using sustainable resources, and using environmental management systems. Given the present environmental difficulties, businesses are encouraged to implement ecologically friendly methods.[18] A CES has been tailored to lessen an organization's environmental impact. The growing study has revealed corporations' commitment to decreasing negative impacts or imprinting beneficial benefits on the environment through the CES.[19]

For companies to achieve sustainability within their organization they need strategies that will improve their business operation. Environmental sustainability takes into account environmental issues and hazards while making decisions that will have a positive influence on the environment. This is done willingly to maintain the company's operation in a strong ethical way and meet the long-term benefits for society, the environment, and stakeholders.[20] Latan *et al.*[6] offered an explanation regarding environmental strategies that they are a collection of ways that, through processes, products, and business practices, can reduce the total ecological effect of operational activities. This includes lowering power use and waste; using green, sustainable technology; and establishing environmental management systems. Xie *et al*.[21] described CES as a collection of voluntary environmental strategies that reflect a company's strategic capability. The three stages of environmental strategies include product stewardship, pollution prevention, and sustainable development as introduced by Hart.[22]

Environmental measures for businesses usually include pollution avoidance and product stewardship.[23] Pollution prevention aims to reduce waste and emissions in company operations by emphasizing waste management beyond control and toward prevention. Preventing pollution drives protecting the natural environment, while product stewardship broadens the focus to cover every aspect of an operation's supply network.[24] Product stewardship legislation, which holds corporations accountable for adverse environmental impacts linked with their products' entire lifespan, is being implemented around the world because companies frequently overlook the costs borne by others until they are compelled by law to accept responsibility for them.[25] The prevention of pollution depends on environmentally friendly innovations that are incorporated throughout the process, decreasing the environmental impacts during manufacturing while also cutting costs, potential risks, and environmental dangers.[23]

CES enhances business commitment, proactive ecological conduct, and the company's ecological sustainability. Thus, a company's achievement in establishing and implementing a corporate environmental policy is primarily contingent on workers' values and behavior.[26] Businesses' environmental strategies often represent how they may reduce negative impacts or improve ecosystem processes through sustainable goods and markets. Thus, green human resource management, the use of environmental management systems, and the reduction of energy consumption and waste will assist in mitigating the detrimental effects.[27] An environmental strategy will direct business policy toward the implementation of an environmental management system, which will incorporate EMA.[28] According to Mokhtar *et al*.,[29] EMA is described as the discovery, allocation, creation, and use of physical and monetary environmental information to assist corporate decision-making to promote long-term profitability. It is a collection of accounting procedures that use data from financial reporting, cost estimation, and material movement balances to increase resource utilization, reduce ecological implications, and lessen environmental protection costs.

In a case study conducted by Latan *et al*.,[6] the results revealed that factors such as organizational assets (business ecological tactics, commitment from senior executives, and ecological incertitude) have a substantial and beneficial impact on EMA implementation that could assist businesses to improve their environmental sustainability. The findings of Papagiannakis *et al*.[12] revealed an emergent perspective of environmental strategy, in which skills that are gradually acquired in tandem with environmental results lead to an upgrade of environmental goals, hence initiating the feedback cycle. Findings from Fraj *et al*.[30] showed that proactive environmental strategies and innovation improve company competitiveness. A study by Kraus *et al*.[9] provides a useful methodology for upper management of industrial firms and lawmakers to analyze the environmental outcomes achieved by managing corporate social responsibility (CSR), ecological plans of action, and innovative environmental practices. Furthermore, it may help upper management in major industrial businesses build internal resources such as CSR, environmental strategy, and green innovation to improve environmental performance.

2.2. Assessing plastic pollution: Ecological consequences and environmental degradation

Plastics have become a key commodity globally because of their outstanding physical and chemical properties, and they have diverse uses in commercial and industrial products. On an international scale, large-scale fiber and resin manufacturing has increased in response to rising societal demand. However, the use of plastics has various severe ecological repercussions arising from their fabrication and inadequate waste management practices.[31] Plastic manufacturing was expected to reach 260 million metric tons globally in 2007. This prediction increased to 359 million tons in 2018 and 400.3 million tons in 2022. Because they generally come as single-use goods and packaging materials, nearly 50% of plastic products fall under the disposable product category.[32]

Inadequate plastic waste disposal procedures are causing problems for the environment and animals. It poses a significant danger to conservation.[33] South Africa manages plastic garbage through recycling and landfilling, with landfills receiving the vast bulk of plastic rubbish. Although some of the plastic debris in landfills is retrieved and repurposed, the rest remains tainted. As a consequence, the overall price of recycling goes up, and plastic is limited to recycling into lower-value commodities.[34] Recycling may contribute to reducing the environmental effect of plastic waste and save finite natural resources (fossil fuels) since the process of plastic production consumes over 8% of the total amount of oil generated internationally.[35] To address the issue, some countries on a global scale have taken a number of steps, including banning SUPs or transitioning from petroleum-based plastics to alternative, safer, more sustainable, and environmentally friendly products such as biodegradable plastic. Improving garbage collection systems to guarantee that plastics are properly collected and securely recycled or disposed of at the end of their useful lives is also one of these initiatives.[36]

Plastic pollution has an influence on aquatic environments, including coral reefs, seagrass meadows, and coastal ecosystems. Plastic trash can choke coral reefs, limiting their ability to recover and maintain marine biodiversity. Plastic garbage has entered terrestrial ecosystems, including soil. Microplastics can build up in soils, compromising soil health and nutrient cycling, potentially leading to lower agricultural output.[37] A growing global consensus has emerged on the vital requirement to shift from a modern sequential take-make-dispose paradigm to a regenerative approach. Plastic items are intended to be recycled or reused in a "symmetrical economy" concept.[38] The hazardous waste management pyramid assesses waste procedures according to their capacity to conserve resources, with waste prevention or reduction being the most ideal future course to pursue, and trash disposal as the most catastrophic event to be prevented regardless of costs.[39]

2.3. Theoretical framework: Institutional theory

This study employs institutional theory to determine the influence of CESs on PPC. The theory of institutions emphasizes the organization's relationship with its surroundings, notably its stability and long-term sustainability. This notion focuses on how organizations may use existing rules and laws to increase their stability and chances of survival. Furthermore, adhering to these standards and rules helps the organization's reputation, as well as the capacity to accept assistance and obtain supplies.[40,41] According to Muhammad Jamil *et al*.[42] institutional theory looks at how organizational factors such as the government, professional bodies, and society affect organizational structure and behavior. Therefore, the isomorphic concept is essential in the field of institutional theory, which often involves the following mechanisms: Coercive, imitative, or socially restrictive factors. The institutional theory employs three isomorphic institutional forces to explain how organizations develop and apply comparable institutional policies, structures, and practices, particularly;[43]

1. *Coercive isomorphism.* It is the outcome of both the formal and informal impacts of legislation and compliance imposed by controlling institutions, such as government regulations
2. *Normative isomorphism.* It is the outcome of membership in social groups and professionalization. It requires organizations to better understand environmental sustainability, embrace new cultural norms and concepts, and respond effectively to environmental concerns
3. *Mimetic isomorphism.* It occurs when an organization implements best practices learned from other organizations that are leading environmental sustainability efforts.

Institutional theory is useful because it addresses institutional variables influencing company and employee behavior.[44] According to institutional theory, legislation, principles, cultural practices, common understandings, conventions, and societal expectations, all have a substantial influence on the structural behaviors and practices of an organization.[45] The institutional theory is suited for business sustainability since sustainable development aspects are governed by policies and agreements. Thus, individual norms and belief systems evaluate a firm's commitment to sustainable development by affecting its acceptability and legitimacy, and stakeholders with conflicting perspectives on corporate sustainability will collaborate to build norms and shared beliefs.[46]

Institutional isomorphism has helped to advance our knowledge of the connection between organizational structure and the larger social environment. Previous researchers have noted that institutions in an organization's surroundings influence their systems, structures, and strategies. The three mechanisms or pressures previously discussed in this section inspire appropriate policies, systems, and procedures, including CESs. Therefore, a study is needed to investigate how F&B manufacturing firms' policies can improve the environmental management of plastic waste, consequently tackling the world's most serious environmental problem – plastic pollution – which affects both land and ocean environments. Given the demand from the government, society, and other stakeholders on businesses to decrease their environmental impact. It is important to analyze what techniques have been applied in these organizations and whether they are possible to improve PPC. Hence, we suggest H1.

The literature review identifies a dearth of extensive research on the impact of corporate environmental policies on plastic pollution reduction, notably in F&B manufacturing businesses and other heavy-polluting industries. A shift in recent research has been observed, as the literature investigates CESs as a tool used by businesses to improve their competitiveness, rather than holding companies accountable for their impact and developing strategies that can be implemented in the organizational structure to address the problem. The purpose of the study is to investigate whether or not CES can influence how F&B's management of plastic pollution. Thereafter, test any association between the variables.

The hypothesis of the study is:

- H_0: CES does not influence PPC in F&B manufacturing firms
- H_1: CES influences PPC in F&B manufacturing firms.

3. Materials and methods

This research employed a positivist research paradigm. Hence, the quantitative technique was adopted in this work. Positivistic philosophers use scientific approaches to standardize the knowledge-generating process and simplify parameter definitions and their relationships.[47] Quantitative research focuses on data presentation, whereas qualitative research focuses on comprehending the presented topic. Quantitative research employs systematic methodologies and formal data-collecting tools. Data were collected objectively and carefully. Finally, statistical approaches were used to investigate numerical data. This is generally achieved using software such as Statistical Package for the Social Sciences (SPSS), R, or Stata.[48] The study focused on Durban-based F&B-producing enterprises. This industry was chosen because they mostly utilize SUP to package their products such as meals, refreshing drinks, water, and other similar things that fall within this category. It is estimated that about 55 companies in Durban manufacture F&Bs.[49]

The sample approach used was convenience sampling, a type of non-probability sampling. Convenience sampling refers to the data gathering method from a study population that is easily accessible to the researcher. Convenience sampling, which simply implies that researchers use a sample that is widely available and accessible, may be used in nearly any research. However, the chosen sampling technique phrase is only used if the availability of participants was the researchers' sole concern in choosing a sample and they could not select from many other demographics and study sites.[50] Therefore, this sampling strategy was used since the researcher needed to use firms that were willing to participate in the study to meet the objectives. Etikan *et al*.[51] confirmed that this strategy is effective when the researcher requires simple access to respondents, availability at a specific time, or willingness to participate in the study.

The sample size for this study was 32 enterprises that make food and drinks multiplied by the four respondents (managers in finance, management, factory, and chief accountants). The sample size for this study was determined as 128 respondents from Durban-based F&B production enterprises. The sample size of manufacturing businesses was sufficient to supply the researcher with sufficient data to carry out the study and meet the objectives. The participants were respondents who were invited to participate in a questionnaire survey and were chosen based on their occupation. The chosen individuals execute comparable duties inside the company and collaborate. Their primary task is to generate financial accounts, predictions, and economic activity reports.

A questionnaire survey was used to collect data, which is a common way of acquiring primary data. Mazhar *et al*.[52] highlighted that unpublished data are more dependable, exact, and impartial. Because such data have not been changed or updated by humans, it is more dependable than secondary material obtained from another source. Primary data were used in this study where close-ended Likert questionnaires were distributed through email to 128 participants. The questionnaire surveys allowed the researcher to obtain exact data, from a specific group of people, on their preferences, opinions, behavior, or factual information. Closed questions are believed to generate quantitative data that are easier to numerically code and statistically evaluate.[53,54] The researcher approached respondents through email and briefed them on the study's topic. The survey participant's email address was retrieved from their website, and each potential participant selected was emailed an invitation to participate. The surveys were written in English, as shown in Table 1 and Appendix 1, which provides a description of how the questionnaires given to participants were constructed. The first component was designed to supply us with crucial information about the background of the study's participants, which was necessary to determine whether or not they would be able to finish the survey

Table 1. Structure of questionnaire

Sections	Question/Information
Section A: Respondents background information	Occupation, years of experience, firm scale, indication of environmental cost and activities
Section B: EMAPs in a firm	Include questions about the implementation of such practices as a corporate environmental strategy, firm environmental-related activities, their perspective of EMAPs, and factors influencing the adoption of EMAPs
Section C: Plastic pollution control	Include questions about plastic pollution measures with a firm, understanding of firms to reduce plastic waste, and barriers to implementing alternative methods of packaging.
Section D: Environmental management practices on plastic pollution control	Include questions about environmental information and environmental costs associated with plastic pollution

Abbreviation: EMAPs: Environmental management accounting practices.

and ensure that we obtained trustworthy and accurate results. The remaining parts focused on questions that helped us understand the organizational structure policies in place to prevent plastic pollution, as well as the businesses' desire to develop such measures. The respondents were expected to read the template and indicate whether or not they agreed to participate by clicking continue. The "continue" button directed them to the survey questions.

The quantitative section was constructed using data from five close-ended Likert scale surveys. The Likert scale is ranked as follows: (1) strongly disagree; (2) disagree; (3) neutral; (4) agree; and (5) strongly agree.

Overall, 128 questionnaires were delivered to responders. However, when the surveys were returned, four were filled incorrectly, resulting in 124 valid replies, with a valid response rate of 96.8%. Survey responses were collected and analyzed using the SPSSs (IBM, SPSS Inc., USA). The data with ordinal values were ranked from one (strongly disagree) to five (strongly agree). The nominal figures were coded as (1) "Yes" or (2) "No" SPSS was used to conduct both descriptive and inferential statistical analyses. Descriptive statistical analysis was used to visualize demographic data distributions with tables, whereas inferential statistical analysis was utilized in correlation analysis, regression analysis, and hypothesis testing.

4. Results

Considering this research focuses largely on correlation testing, the data were statistically evaluated to assess the hypothesis. Data were collected quantitatively using SPSS. Pearson correlation coefficient and regression analysis were utilized to assess the relationship between CES and PPC.

4.1. Demographic analysis

Table 2 indicates the respondents' background. Demographic data provides data about research and is necessary to establish if the persons in the investigation are an accurate reflection of the target population for the sake of generalization.

The respondents to this study were managers in finance, management, factory, and chief accountants. Over 70% of the participants had more than 10 years of work experience. This indicated that the respondents were knowledgeable about these elements discussed in the study. The firm's size ranged from small to medium to big, with 70.2% indicating that they incur environmental expenditures and 84% investing in environmental initiatives.

4.2. Measurement model results: Reliability and validity

Exploratory factor analysis (EFA) is a multivariate statistical approach that is commonly employed in quantitative research and is now being applied in a variety of domains, including social sciences, health sciences, and economics. EFA allows researchers to focus on fewer elements that explain the structure rather than too many variables that may be insignificant, and to carry out their investigations by categorizing these items (factors).[55] The study used the EFA approach to find the unobserved (*i.e.*, latent) components. The Kaiser–Meyer–Olkin (KMO) test established by Kaiser and Cronbach's alpha test was employed as a diagnostic test to assess sample adequacy and internal consistency across all questionnaire replies or items.

Individual indicators were checked for reliability by examining item loadings on the respective construct value of the factor loading (Table 3).

The Croncbach's alpha coefficient for each scale was calculated to measure the internal consistency

Table 2. Demographic information

Item	Description	Frequency	Percentage
Job designation	Financial manager	31	25
	Management accountant	32	25.8
	Factory accountant	31	25
	Chief accountant	30	24.2
Employment experience	0–5 years	11	8.9
	6–10 years	25	20.2
	11–15 years	36	29
	16–20 years	36	29
	>21 years	16	12.9
Firm scale	Small	57	46
	Medium	39	31.5
	Large	28	22.6
Environmental costs	Yes	87	70.2
	No	37	29.8
Environmental activities	Yes	84	67.7
	No	40	32.2

Table 3. Reliability and validity results from exploratory factor analysis

Constructs	Items	Loading	Cronbach's alpha	Eigenvalue	Variance
CES	CES1	0.667	0.719	2.793	5.270
	CES2	0.587			
	CES3	0.590			
	CES4	0.580			
PPC	INF2	0.599	0.869	3.548	6.694
	INF8	0.667			
	INF9	0.681			
	PPC1	0.624			
	PPC3	0.572			
	PPC4	0.500			
	PPC6	0.566			
	ERA6	0.567			

Notes: KMO=0.774; χ^2=5449.334; df=1378; p<0.001.
Abbreviations: CES: Corporate environmental strategy; ERA: Environmental related activities; INF: Environmental information; PPC: Plastic pollution control.

of factors. According to Shrestha[56] Cronbach's alpha measures a questionnaire's reliability. It gives a straightforward approach to determining whether a score is credible. It assumes several items measure the same underlying notion. Cronbach's alpha is a measurement of internal consistency. It is also regarded as a metric of scale dependability. Cronbach's alpha varies from 0 to 1. In general, Cronbach's alpha values >0.7 are regarded as acceptable. However, other scholars have highlighted that an item with a Cronbach's alpha score of >0.6 (acceptable between 0.6 and 0.8) and a corrected item-total correlation larger than 0.3 is regarded as trustworthy.[57] During this phase of analysis and as illustrated in Table 3, the internal consistency of constructs (all relative) was examined, and composite reliability values of both constructs exceeded 0.70, which suggests moderate (acceptable) reliability CES and PPC scores of 0.719 and 0.869, respectively. The next phase requires establishing the validity of each construct, which is indicated by the variance, and as illustrated in Table 3 above, the variances have a value of 0.5 and higher. This indicates that the construct explains at least 50% or more of the variation in the components that comprise it. Results presented in Table 2 confirm the variance values are within the recommended threshold. The KMO test result of 0.77 suggests that the research sample size of 124 is adequate. The Bartlett test of sphericity, which explains why EFA was performed, is statistically significant ($p < 0.001$).

4.3. Pearson correlation coefficient and regression analysis

4.3.1. The relationship between CES and PPC

The outcome of the statistical analysis is shown in Table 4. This table illustrates a correlation between CESs and PPC.

Table 4 shows a substantial link between CES and plastic pollution reduction in F&B manufacturing enterprises (r = 0.385, $P < 0.0005$). The significant relationship suggests a direct link between the two constructs. This means that, as CES improves within an organization, they will be able to address or control plastic pollution to a greater extent.

An examination of regression was performed to determine the amount of influence between the two components. Table 5 shows the linear regression results.

The regression study, presented in Table 5, yielded an R^2 value of 0.149, implying that business environmental policy accounted for 14.9% of the variation in PPC. The R^2 score indicates how much of the overall variance in the dependent variable (PPC) can be explained by the independent variable (CES). There is a substantial linear link between environmental knowledge and plastic pollution prevention, with $F(1,122) = 21.286$; $p < 0.0005$. A $p < 0.0005$ suggests a significant relationship between the independent variable (CES) and the dependent variable (Plastic Pollution Reduction), with B = 0.385 and $p < 0.0005$. The results confirmed the hypothesis of the study.

5. Discussion

The purpose of this study was to investigate the impact of CES on plastic pollution management in F&B manufacturing enterprises. The study's goal was to examine if any variations applied inside the organizational structure may have an impact on waste management. The study focused on the F&B industries because of their excessive usage of SUP packaging. The findings of the study found a significant relationship between CES and PPC, and the proposed hypothesis was confirmed. A study conducted by Wang *et al*.[58] revealed that stakeholder pressures may have a greater impact on CESs in developed nations and non-manufacturing enterprises maybe can easily adapt their environmental strategy than manufacturing firms. Although the firms might be willing to implement the strategies for manufacturing companies might find it difficult to do so as the means altering the entire processes at all levels. However, the finding of Zeng *et al*.[59] contradicts this because heavy-polluting companies are likely to incorporate prevention strategies.

Our study's finding aligns with the results obtained by Aftab *et al*.[60] that revealed that CES strengthens and drives sustainable innovation within an organization. Furthermore, the findings indicate the necessity for senior organizational management to strengthen their commitment to environmental ethics by developing and implementing diverse environmental practices in day-to-day operations to successfully address critical sustainability concerns. Kuo *et al*.[61] found that CESs have a favorable impact on sustainable innovation. The results obtained in this study and the previous scholarly empirical research indicated that enhancing CES improves sustainable measures such as developing new environmentally friendly products, greener operations, and processes. The outcomes of Javeed *et al*.[62] revealed that firms with business environmental strategies such as environmental regulation, proactive environmental

Table 4. Relationship between corporate environmental strategy and plastic pollution control

Construct A	Construct B	Pearson's correlation (r)	*p*
Corporate environmental strategy	Plastic pollution control	0.385**	<0.0005

Note: **The association becomes statistically significant at the 0.01 level (two-tailed).

Table 5. Linear regression between corporate environmental strategy and plastic pollution control

Variables in the equation	B	Beta	t	*P*	R^2	F	df	*p*
Constant	14.848		5.919	<0.0005	0.149	21.286	1; 122	<0.0005
Corporate environmental strategy	0.824	0.385	4.614	<0.0005				

Note: Dependent variable: Plastic pollution control; Predictor (Constant): Corporate environmental strategy.

planning, CSR, and board sustainability committees were more likely to employ green innovation methods.

A study by Aragón-Correa and Sharma[63] on CES highlighted that proactive CESs are a type of pollution prevention technology investment (rather than reactive investment in pollution control). As a result, it only resulted in environmental and competitive improvements linked to the development of specific strategic managerial and manufacturing processes. However, Wagner and Schaltegger[64] found that firms with pollution-prevention-focused CESs outperform in terms of both environmental and economic performance.

Mårtensson and Westerberg[13] have suggested guidelines for developing a long-term environmentally sustainable strategy that minimizes ecological influence while also providing a foundation for competitive advantage in a world where environmental concerns are becoming progressively essential in different decision-making cases. In practice, a strategy that concentrates on reducing the environmental impact of a production system is achieved using raw materials productively, lessening the use of harmful/toxic materials, and integrating waste into a recirculation system. According to the empirical results obtained by Wang *et al*.[65] companies that are not involved in the production of goods can easily change their ecological strategies compared to those that do. Thus, pressure placed by different stakeholders on organizations in developed countries may greatly affect the company's environmental strategies. The findings have significant relevance because an eco-friendly industry transition is deemed necessary in the manufacturing sector, particularly in highly polluting companies. In addition, these companies should implement environmental strategy within the organizational structure for a more sustainable future.

Therefore, this study concludes that having CESs within the organization can lead to better plastic pollution prevention measures. According to Frajrdingno *et al*.[66] The competitive advantage gained from developing ecological strategies and ecological products motivates a company's ability to instill the value of environmental protection throughout the company.

6. Conclusion

With a growing interest in sustainable practices, many organizations seek to demonstrate their commitment to being accountable for their environmental effect. However, according to the research, compliance is motivated mostly by the need to establish a good reputation and remain competitive in the industry. These firms do not employ sustainable practices at the organizational level or in their day-to-day operations. The study aimed to examine the influence of CES on PPC in F&B manufacturing firms. The CES was analyzed as an environmental management tool that can be used to develop measures that could reduce these companies' impact on the environment.

Using the Pearson correlation coefficient, the findings of the study confirmed the hypothesis and showed a positive and significant relationship between CES and PPC. The findings indicated that as CES improves, plastic pollution will consequently also improve. A further linear regression analysis was conducted and also revealed a favorable and significant relationship between the two variables. Thus, the regression analysis yielded an R^2 value of 0.149, indicating that CES explains 14.9% of the variation in PPC. It can be concluded that when a company implements CESs as an environmental management tool better measures can be developed and implemented to control plastic waste pollution. If the companies implement the strategies at an organizational level, the business will always account for their environmental impact, and it will assist management in decision-making.

The results raise the intriguing win-win prospect and have significant implications for the environmental policy maker, government, and F&B companies (managers) that want to embark on a sustainable business operation. The current research underlined the importance of implementing CES in an organization and increased our understanding of how it could potentially influence the development of an improved plastic pollution measure. Although instigating transformation for developing countries could be lengthy, this study adds to the literature and provides guidance for F&B companies to engage in sustainable practices such as using alternative greener packaging methods. Integrating environmental management into corporate plans can create a competitive advantage and fulfill customer expectations for sustainability.

Using diverse management techniques at different stages of environmental plan creation can enhance cost-effectiveness and resource sustainability.[67] The government can play a huge role in encouraging top management to integrate sustainable practices in their businesses through incentives or tax rebates. Enterprises recognize the critical role of green development by promoting eco-friendly practices and identifying possibilities in government legislation.[68]

Using convenience sampling posed a limitation to the study as we had to use companies that were willing to take part in the study and limited our sampling to the selected F&B companies in this developing country. This meant we could not generalize our findings to a developed nation as compared to a developing country. Hence, further research is required on the same topic to benchmark the results with developed nations. There are several areas for further investigation. Another drawback is that the study is mostly descriptive, focusing on correlations rather than causal relationships. A longitudinal study to track the progress of firms' environmental strategy and instruments over time should be considered. A comparison analysis with corporations from other countries would be beneficial to understand the impact of national and cultural variations on sustainability initiatives. Future studies should focus on panel data and exogenous interventions to better understand cause and effect in this particular topic. Examining the application of technical breakthroughs such as artificial intelligence and digitalization in environmental management might help promote sustainability.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: All authors
Investigation: All authors
Methodology: All authors
Supervision: Odunayo M. Olarewaju
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Availability of data

Not applicable.

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Appendix

Appendix 1. Questionnaires

Section A: Biographic information

1. **Job designation**
    - ☐ Financial Manager
    - ☐ Management Accountant
    - ☐ Factory Accountant
    - ☐ Chief Accountant

2. **Employment experience**
    - ☐ 0 – 5 years
    - ☐ 6 – 10 years
    - ☐ 11 – 15 years
    - ☐ 16 – 20 years
    - ☐ >21 years

3. **Firm scale**
    - ☐ Small
    - ☐ Medium
    - ☐ Large

4. **Existence of environmental costs**
    - ☐ Yes
    - ☐ No

5. **Investments on environmental activities**
    - ☐ Yes
    - ☐ No

Section B: Environmental management accounting practices in a firm						
S/N	**Statements**	**SD**	**D**	**N**	**A**	**SA**
1.1	Corporate environmental strategy of firm:					
1.1.1	Our organization values environmental sustainability.					
1.1.2	Environmental concerns are included in the company's strategic planning mechanism.					
1.1.3	Environmental aims are tied to the organization's strategic objectives.					
1.1.4	Environmental problems are often taken into consideration while developing new goods.					
1.1.5	The present financial management/costing system provides the organization with the information needed to analyze environmental costs.					
1.2	Environmental related activities:					
1.2.1	The organization regulates environment-related expenditures.					
1.2.2	The organization allocates environmental expenses to industrial processes.					
1.2.3	The organization assigns environmental costs to products.					
1.2.4	The organization creates an environment-related expenditure account when making decisions.					
1.2.5	The organization utilizes a cost of sustainability account.					
1.2.6	The organization improves costs related to environmental control.					
1.3	Perspectives of environmental management accounting:					
1.3.1	The existing management accounting system discloses environmental information.					
1.3.2	Proper accounting methods are provided when dealing with a particular issue related to the environment.					
1.3.3	The organization conducts environmental impact audits to examine the organization's influence on the environment arising from economic activity.					
1.3.4	The organization reports environmental information to external stakeholders.					

Abbreviations: SD: Strongly disagree (1); D: Disagree (2); N: Neutral (3); A: Agree (4); SA=Strongly agree (5)

Section C: Plastic pollution control						
S/N	**Statements**	**SD**	**D**	**N**	**A**	**SA**
2.1	Plastic pollution control within the firm:					
2.1.1	The majority of the items created have a brief life.					
2.1.2	Most of our short-lived items are constructed of plastic.					
2.1.3	Our finished items are packed using single-use plastic packaging.					
2.1.4	The organization supports several plastic recycling designs.					
2.1.5	Customers are encouraged by the company to adopt environmentally responsible activities.					
2.1.6	Minimizing plastic waste also requires an effort from the customer.					

Abbreviations: SD: Strongly disagree (1); D: Disagree (2); N: Neutral (3); A: Agree (4); SA: Strongly Agree (5)

Section D: Environmental management practices on plastic pollution control						
S/N	**Statements**	**SD**	**D**	**N**	**A**	**SA**
3.1	Environmental information and environmental costs associated with plastic pollution					
3.1.1	The organization reports the environmental costs connected with plastic contamination.					
3.1.2	Major environmental expenditures spent by the corporation pertain to the avoidance of plastic contamination.					
3.1.3	The organization strives to lessen the hazard of plastic waste to the environment by applying environmental management accounting tools.					
3.1.4	The organization identifies environmental expenses related to plastic using environmental management accounting techniques.					
3.1.5	The organization uses environmental management accounting systems to track the environmental expenses connected with plastic.					
3.1.6	The organization records the environmental expenses connected with plastic using environmental management accounting systems.					

Abbreviations: SD: Strongly Disagree (1); D: Disagree (2); N: Neutral (3); A: Agree (4); SA: Strongly Agree (5).

Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 99-114.
doi: 10.36922/AJWEP025040023

ORIGINAL RESEARCH ARTICLE

Assessment of groundwater quality in Borana Zone, Ethiopia: A multidimensional analysis using groundwater pollution index, nitrate pollution index, and water quality index

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Received: January 23, 2025; Revised: February 26, 2025; Accepted: February 27, 2025; Published Online: March 14, 2025

Abstract: This study assessed groundwater quality in Yabelo, Elewaye, Gomole, and Duduluk towns in Ethiopia, analyzing 60 samples across 19 physicochemical parameters. The groundwater pollution index (GPI), nitrate pollution index (NPI), and water quality index (WQI) were used to evaluate drinking water suitability. Results showed turbidity, pH, bicarbonate, nitrite, and copper levels were within the World Health Organization recommended limits. However, 20% of the samples had high total dissolved solids and sulfate levels. Total hardness exceeded limits in 60% of the samples, and 40% had elevated nitrate concentrations. Chromium and fluoride were elevated by 10%, while total iron and manganese exceeded standards by 20%. The GPI indicated "Insignificant pollution" in 80% of samples and "Low pollution" in 20%. Among the samples, the NPI classified 50% as "Clean", 10% as "Low pollution", 30% as "Moderate", and 10% as "Very high pollution". The WQI rated 20% as "Good", 30% as "Very good", and 50% as "Excellent". This study provides valuable insights to help authorities in identifying protective measures and treatment methods for water resources.

Keywords: Borana Zone; Drinking water; Ethiopia, Groundwater; Groundwater pollution index; Nitrate pollution index; Physicochemical parameter; Water quality index

1. Introduction

Water is essential for life; without it, existence is impossible.[1] Groundwater is becoming an increasingly vital source of drinking water worldwide, as surface water is increasingly affected by pollution and climate change.[2,3] It is estimated that only 3% of Earth's water is freshwater, with 2.97% of this being locked in ice caps and glaciers, leaving only 0.03% available as surface and groundwater for human use.[4] In both urban and rural areas worldwide, groundwater serves as a crucial source of water for household consumption.[5] Water contamination can result from both anthropogenic sources, such as industrial activities, agricultural practices, improper waste disposal, and inadequate sewage systems, as well as natural sources, including microbial activity, geological factors, and naturally occurring contaminants.[6] To ensure water is safe for consumption, it is crucial to assess its quality, as potable water must be free from physical, chemical, and biological contaminants.[7]

Most people in developing nations obtain their drinking water from unprotected or contaminated sources, which heightens the risk of outbreaks of waterborne diseases.[8] Efforts to prevent and control waterborne diseases continue to depend on the quality of drinking water, which serves as a vital environmental indicator of public health.[9] Waterborne diseases, such as dysentery, cholera, diarrhea, and typhoid are caused by the consumption of contaminated water and can lead to pre-mature death, particularly in developing countries.[10]

Ethiopia has the lowest rate of access to safe drinking water among sub-Saharan African nations.[11] In recent times, the demand for water and subsequent groundwater abstraction has increased across Ethiopia, as surface water bodies have become increasingly prone to pollution.[12] Although the government does not have regular and comprehensive water quality testing programs, there are growing concerns about the pollution of both surface and groundwater sources in some areas.[4]

Evaluating water quality based on the concentrations of various components can be challenging.[3] To effectively summarize water quality while preserving scientific integrity, the water quality index (WQI) method is highly valuable.[13] The WQI serves as a powerful tool for conveying groundwater quality information to the public and policymakers. Its primary objective is to transform complex water quality data into understandable and actionable information, focusing on the suitability of groundwater for human consumption.[14] This index assigns a single value that reflects the overall water quality at a specific location and time, based on a range of water quality parameters. It also enhances the interpretability of these parameters and facilitates comparisons across different sampling sites.[15,16] Conversely, the groundwater pollution index (GPI), developed by Rao,[17] is another methodology used to assess groundwater quality. The GPI has been effectively applied in monitoring drinking water quality in various regions, as shown in studies by Sanad *et al.*[13] and Al-Aizari *et al.*[18] On the other hand, the nitrate pollution index (NPI) is a numerical value used to assess the extent of nitrate contamination in groundwater.[19]

However, limited studies in Ethiopia have assessed groundwater quality using the WQI, GPI, and NPI. Even more concerning is the absence of such studies in the Borana Zone of the Oromia region, an arid area where access to fresh drinking water remains a significant challenge and groundwater serves as the primary source of drinking water. Despite its significance, the physicochemical quality of groundwater sources in the Borana Zone, particularly in the towns of Yabelo, Dubuluk, Elewaye, and Gomole, has not been thoroughly studied.

Therefore, this exploratory study aimed to: (1) assess the physicochemical properties of groundwater sources in the Borana Zone, particularly in the towns of Yabelo, Dubuluk, Elewaye, and Gomole; and (2) conduct a comprehensive evaluation of groundwater quality in the designated study area using the WQI, GPI, and NPI techniques to assess its suitability for drinking.

This comprehensive approach provides a holistic perspective on groundwater quality and its implications for the suitability of drinking water sources, while also enabling the identification of associations between groundwater characteristics and their potential impacts on human health. Comprehending the complex relationships between groundwater quality and the suitability of drinking water is crucial for developing effective water resource management strategies. Moreover, it is crucial for minimizing the undesirable impacts of deteriorating water quality on water use and eventually human well-being.

1.1. Description of the study area

The Borana Zone of the Oromia region is located in the southernmost part of Ethiopia (Figure 1), bordering the West Guji Zone to the north, Kenya to the south, the Guji Zone and Somali Regional State to the east, and the Southern Nations region to the west. Its geographical location is 3°30′N – 5°25′N latitude and 36°40′E – 39°45′E longitude. The area is characterized by a semi-arid to arid climate and is primarily inhabited by pastoral and agro-pastoral Borana communities. The town of Yabelo, located 575 km south of Addis Ababa along the route to Moyale-Kenya, is the administrative seat of the Borana Zone. The zone covers an area of approximately 95,000 km^2, with 75% classified as lowland, and has an overall population density of six inhabitants per square kilometer.[20,21]

The Borana Zone's ephemeral drainage system is located within the Genale-Dawa River Basin. Groundwater levels in the study area are generally deep, and there are no perennial rivers. Rainfall in the zone is highly variable, both spatially and temporally. As a result, rural communities in Borana Zone have limited access to clean drinking water. The primary water sources for pastoralists in the area include open surface water, such as runoff, floodwater, ponds, and micro-dams, as well

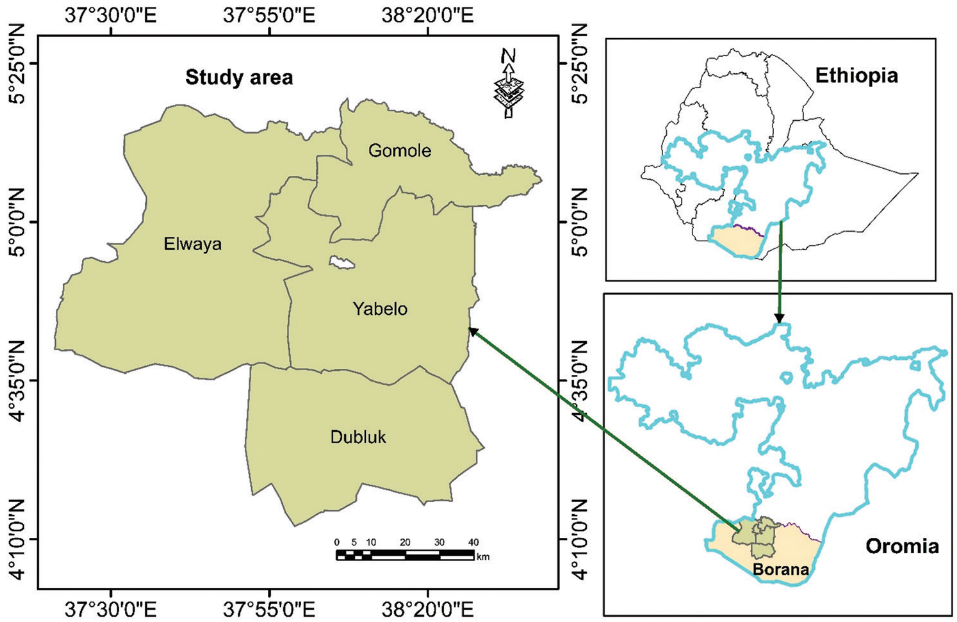

Figure 1. Location map of the study area showing the locations of Yabelo, Dubluk, Elwaya, and Gomole

as groundwater sources, such as boreholes, shallow wells (locally known as "Adadi" or "Tula wells"), and motorized pumps. These water sources are used for both domestic purposes and livestock consumption, depending on the season. During the wet season, runoff and floodwater are used, whereas ponds, boreholes, and micro-dams become the primary water sources during the dry season. The remaining water sources are mainly used during periods of drought.[22,23]

2. Materials and methods

2.1. Water sampling and preservation

In addition to Yabelo Township, which includes Borana University, the water sampling process encompassed three surrounding towns: Elewaye, Dubluk, and Gomole (Figure 1). These towns were selected using a purposive sampling method, based on the community concerns and dissatisfaction with the quality of some available ground water sources for drinking. The study included all four borehole sources that supply drinking water to Yabelo town, as well as two randomly selected groundwater sources from each Elewaye, Dubluk, and Gomole towns (Table 1). In total, water samples were collected from ten sampling sites, as outlined in Table 1.

Water samples were collected in 1 L polyethylene plastic bottles from June to August 2023, with a 2-week interval between each collection, to analyze nineteen physicochemical parameters, following the methodologies outlined by Gintamo *et al.*,[24] and Garoma *et al.*[25] Before sampling, the bottles were thoroughly cleaned using detergents according to the protocol described by Gebresilasie *et al.*[5] The bottles were then treated with 5% nitric acid (HNO_3) (Nanjing Taibai Chemical Co., Ltd, China) and left to acidify for 24 h. After acidification, the bottles were rinsed twice with distilled water and subsequently rinsed 3 times with sample water before being filled with the groundwater sample.

A total of 60 water samples were collected from 10 different sampling sites (Table 1), with two bottles per site during each sampling event, and each sampling event repeated 3 times. The first bottle was acidified with HNO_3 for major ion analysis, while the second bottle remained unacidified for the analysis of other physicochemical parameters.[26,27] To ensure the samples accurately reflect the groundwater chemistry, the water volume was flushed at least twice during pumping to obtain fresh groundwater before sampling, as described by Sanad *et al.*[13]

Each sample bottle was labeled with a unique sample code and stored at 4°C in a dark place to maintain stable conditions until analysis.[19,28]

2.2. Analysis of water samples

2.2.1. Determination of physical parameters

Temperature, turbidity, pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured *in situ* at each sampling site. Water temperature was measured using a mercury thermometer (Jiangsu Exact

Table 1. Description of groundwater sampling sites of the study area

Sampling site	Location/town	Description of sampling site
Y1	Yabelo	Dollolo Hola deep tube well 1
Y2	Yabelo	Dollolo Hola deep tube well 2
Y3	Yabelo	Garbi spring water
Y4	Yabelo	Mebiratu private deep tube well
E1	Elewaye	China-constructed deep tube well
E2	Elewaye	Turk-constructed deep tube well
S1	Gomole	Protected Hund dung well ("Tula well")
S2	Gomole	Goro Gudina shallow tube well
D1	Dubuluk	Ali scheme shallow tube well
D2	Dubuluk	Manhariya scheme shallow tube well

Instrument Technology Co., Ltd. China), which was calibrated using the ice-water method. Turbidity and pH were determined using a portable turbidity meter (Model 2100Q, HACH, USA) and a portable pH meter (Model HI9024, HANNA Instruments, Italy), respectively. The turbidity meter was calibrated using turbidity standards of 0.5, 10, and 20 NTU, prepared by diluting precise volumes of a 100 NTU Stablcal Stabilized Formazin Turbidity Standard solution (HACH, UK) with deionized water in a volumetric flask. Meanwhile, the pH meter was calibrated using standard buffer solutions of pH 4.01, 7.01, and 10.01, ensuring coverage of a broad pH range.[29] The EC and TDS were measured using a portable digital multi-parameter meter (Model HQ440D, HACH, USA) after calibrating with the Myron L KCl-1800 Conductivity/TDS standard solution (Myron L Company, USA), which has a potassium chloride (KCl) concentration equivalent to 1800 µS/cm.

2.2.2. Determination of chemical parameters

The chemical composition of the drinking water samples was analyzed for the following parameters: bicarbonate (HCO_3^-), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), total hardness (TH), total alkalinity (TA), sulfate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), copper (Cu^{2+}), manganese (Mn^{2+}), total iron (total Fe), fluoride (F^-), and chromium (Cr^{6+}). These tests were conducted at the drinking water quality control laboratory of the Oromia National Regional State in Addis Ababa, Ethiopia. The concentrations of K^+, SO_4^{2-}, NO_3^-, NO_2^-, PO_4^{3-}, Cu^{2+}, Mn^{2+}, total Fe, F^-, and Cr^{6+} were measured using a ultraviolet-visible (UV-Vis) spectrophotometer (DR6000, HACH, USA), following the standard procedures outlined by American Public Health Association.[30] The methods and reagents employed for analyzing the parameters using the DR 6000 UV-VIS spectrophotometer are outlined in Table 2. Sample cup 9418100 was used for phosphate testing, while sample cell 2495402 was used for testing the other parameters, utilizing reagent powder pillow additions, with both tests conducted using the DR 600 UV-Vis spectrophotometer.

Ca^{2+}, Mg^{2+}, and total hardness (TH) levels were determined using complexometric titration with ethylene diamine tetra acetic acid (EDTA) (Henan Honghai Chemical Co., Ltd, China) in the presence of the eriochrome black T (EBT) indicator (Sigma-Aldrich, China).[13,19,24] Bicarbonate (HCO_3^-) concentration of the water sample was measured using a titrimetric method with a standard sulfuric acid solution, along with a mixed indicator solution (Sigma-Aldrich, China) of bromocresol green and methyl red, which turned pink at the endpoint of the titration.[16,31] The total alkalinity (TA) of the water sample was calculated based on its bicarbonate (HCO_3^-) concentration. For the analysis of Cu^{2+}, total Fe, Mn^{2+}, and Cr^{6+}, the water samples were initially digested to eliminate organic impurities and prevent interference during the analysis.[7] Concentrated nitric acid (*DFPCL, India*) was used for digestion, in accordance with a published methodology.[5]

2.3. Determination of GPI

The GPI, developed by Rao,[17] is a methodology designed to assess groundwater quality. The calculation of the GPI follows five key steps, as demonstrated in the study by Sanad *et al.*[13] In the first step, individual water quality parameters were assigned weights (w_i) ranging from 1 to 5, based on their significance in determining the overall quality of groundwater and their potential impact on human health. These weights, as outlined in

Table 2. Methods and reagents used for chemical composition analysis using the ultraviolet-visible spectrophotometer

Parameter	Test method	Method number	Sample cell/ cup number	Reagent	Test range* (mg/L)
K^+	Tetraphenylborate	8049	2495402	Potassium 1 Reagent Powder Pillow	1.0 – 70.0
Cu^{2+}	USEPA[1,2] and bicinchoninate method[3]	8506	2495402	CuVer® 1 Copper Reagent Powder Pillow	0.04 – 5.00
Total Fe	USEPA[1] and FerroVer® method[2]	8008	2495402	FerroVer® Iron Reagent	0.02 – 3.00
Mn^{2+}	USEPA[1] and periodate oxidation method[2]	8034	2495402	Sodium Periodate and Manganese powder pillows	0.1 – 20.0
Cr^{6+}	USEPA[1] and 1,5-diphenylcarbohydrazide method[2]	8023	2495402	ChromaVer ® 3 Chromium Reagent Powder Pillows	0.010 – 0.700
NO_3^-	Cadmium reduction	8039	2495402	NitraVer® 5 Nitrate Reagent Powder Pillow	0.3 – 30.0
NO_2^-	USEPA diazotization method[1]	8507	2495402	NitriVer® 3 Reagent Powder Pillows	0.002 – 0.300
SO_4^{2-}	USEPA[1] and SulfaVer 4 method[2]	8051	2495402	SulfaVer® 4 Reagent Powder Pillows	2.0 – 70.0
PO_4^{3-}	Phosphomolybdate (ascorbic acid) method[1]	10279	9418100	Phosphate Low Range Chemkey® Reagents	0.02 – 4.00
F^-	USEPA SPADNS method[1]	8029	2495402	SPADNS Fluoride Reagent AccuVac® Ampuls	0.02 – 2.00

Notes: *The ranges given are for the pre-calibrated instrument readout. For sample sites where the concentrations of the parameters under investigation exceeded the upper quantification limit of the analytical method, the samples were diluted with deionized water to reduce the concentrations within the test range of the method.
Abbreviation: USEPA: United States Environmental Protection Agency.

Table 3. The weight assigned to each parameter for GPI calculation in previous studies and the present study

Parameter	Berhe[12]	Sanad *et al.* [13]	Al-Aizari *et al.* [18]	Panneerselvam *et al.* [19]	Ha *et al.* [32]	Present study
TDS	-	2	4	4	5	5
pH	-	4	4	4	4	4
HCO_3^-	1	2	-	3	2	1
K^+	2	3	1	-	2	2
Mg^{2+}	3	3	2	2	3	3
Ca^{2+}	3	3	2	2	3	3
TH	-	3	4	-	4	4
SO_4^{2-}	5	4	5	4	5	5
NO_3^-	5	5	5	5	5	5
PO_4^{3-}	1	4	-	-	-	1
Cu^{2+}	2	-	-	-	-	2
Total Fe	4	-	-	-	-	4
F^-	5	-	-	4	-	5

Abbreviations: TDS: Total dissolved solids; TH: Total hardness.

Table 3, were determined based on previous studies by Berhe,[12] Sanad *et al.,*[13] Al-Aizari *et al.,*[18] Panneerselvam *et al.,*[19,] and Ha *et al.*[32]

In the second step, the relative weight (W_i) (Table 4) for each parameter is calculated using Equation I, as described by Panneerselvam *et al.*[19]

$$Wi = \frac{wi}{\sum_{i=n}^{n} wi} \quad (I)$$

Where W_i is the relative weight, w_i is the weight of each parameter, and n is the number of parameters selected.

In the third step, the concentration status (Sc) for each parameter was calculated by dividing the concentration of individual chemical variables in each water sample by the corresponding drinking water quality standards (WQS) set by the World Health Organization (WHO),[33,34] using Equation II, as described by Al-Aizari *et al.*[18] In the fourth and fifth steps, the overall chemical quality of the water (Ow) and the GPI were assessed using Equations III and IV, respectively, as outlined by Sanad *et al.*[13]

$$Sc = \frac{C}{WQS} \quad (II)$$

where Sc is the concentration status, C is the concentration of individual physicochemical water quality parameters in each water sample and WQS is the drinking water quality standard of each physicochemical parameter set by the WHO.[33,34]

$$Ow = Wi \times Sc \quad (III)$$

where Ow is the overall chemical quality of the water, Wi is the relative weight, and Sc is the concentration status.

$$GPI = \sum_{i=n}^{n} Ow = \sum_{i=n}^{n} Wi \times Sc \quad (IV)$$

where GPI is the groundwater pollution index, Ow is the overall chemical quality of water and n is the number of parameters selected.

2.4. Determination of NPI

The NPI is a key indicator used to assess the level of nitrate contamination in groundwater. It plays a crucial role in evaluating water pollution caused by nitrates, particularly in areas impacted by human activities.[18] The NPI was calculated using Equation V, as outlined by Sanad *et al.*[13] Although the WHO guidelines[34] recommend a maximum nitrate concentration of 50 mg/L in drinking water, the human acceptable value (HAV) for nitrates is set at 20 mg/L. This threshold, supported by studies conducted by Sanad *et al.,*[13] Al-Aizari *et al*.,[18] and Panneerselvam *et al.,*[19] was used for calculating the NPI in the present study.

Table 4. The WHO standards[33,34] for drinking water quality, assigned wi, and calculated Wi for each parameter

Parameters	WQS	Wi	Wi
TDS	1000	5	0.114
pH	7	4	0.091
HCO_3^-	500	1	0.023
K^+	12	2	0.045
Mg^{2+}	50	3	0.068
Ca^{2+}	75	3	0.068
TH	500	4	0.091
SO_4^{2-}	250	5	0.114
NO_3^-	50	5	0.114
PO_4^{3-}	5	1	0.023
Cu^{2+}	2	2	0.045
Total Fe	0.3	4	0.091
F^{--}	1.5	5	0.114
		=44	=1

Abbreviations: WHO: World health organization; WQS: Water quality standards; TDS: Total dissolved solids; TH, Total hardness; wi: Weight values; Wi: Relative weight. Note: The pH value is reported in pH units, while concentrations of all other parameters are expressed in mg/L.

$$NPI = \frac{Cs - HAV}{HAV} \quad (V)$$

where NPI is the nitrate pollution index, Cs is the nitrate concentration in the groundwater (mg/L), and HAV denotes the human acceptable value for nitrate and is taken as 20 mg/L. The NPI values for all groundwater samples were then classified into one of five categories, as shown in Table 5.

2.5. Determination of WQI

The groundwater quality in the study area was assessed using the standard WQI model. This model was selected due to its widely recognized, standardized approach, which ensures consistent and reliable results across various studies and regions, thereby facilitating direct comparisons with other research findings.[3] The WQI calculation includes thirteen physicochemical

Table 5. Results of groundwater quality assessment in the ten sampling sites

Parameter	Sampling sites										Min.	Max.	ESA	WHO
	Y1	Y2	Y3	Y4	E1	E2	S1	S2	D1	D2				
Temperature	27	26.3	26.9	27.1	27	26.7	28.2	28.3	28.6	28.3	26.3	28.6	NGL	<15
Turbidity	0	0	0	0	2	1	1	4	0	0	0	4	5	5
TDS	701	582	99	626	346	326	371	144	1930	1560	99	1930	1000	1000
pH	6.96	6.46	6.39	6.51	8.11	6.78	6.92	6.25	6.38	6.62	6.25	8.11	6.5 – 8.5	6.5 – 8.5
HCO_3^-	178.2	134.2	217.2	190.3	273.3	297.7	164.7	158.6	366	439.2	134.2	366	NGL	500
TA	146	110	178	156	224	244	135	130	300	360	110	360	200	120
K^+	4.4	3.6	1.2	4.3	6.5	4.7	9.50	4.0	46.25	38.75	0.9	46.25	1.5	12
Mg^{2+}	21.12	52.8	9.12	6.24	5.76	27.36	4.80	16.8	79.2	74.4	4.80	79.2	50	50
Ca^{2+}	159.2	112	22.2	158.4	40.8	80.0	88	40	284	220	22.2	284	75	75
TH	486	500	96	422	126	314	240	170	1040	960	96	1040	300	500
SO_4^{2-}	210	122	2.5	140	17	3	62.5	11	360	325	2.5	360	250	250
NO_3^-	100.8	59.4	2.2	58.52	3.52	3.53	4.40	3.08	58.96	36.94	2.2	100.8	50	50
NO_2^-	0.003	0.003	0.005	0.008	0.006	0.004	0.006	0.009	0.006	0.008	0.003	0.009	3	3
PO_4^{3-}	0.35	0.38	0.21	0.2	0.28	0.2	0.70	1.22	0.22	0.30	0.2	1.22	NGL	5
F^-	1.01	0.98	0.32	1.18	2.52	0.59	0.43	0.40	1.19	1.29	0.32	2.52	1.5	1.5
Cu^{2+}	0.65	0.45	0.08	0.69	0.05	0.62	0.07	0.09	0.15	0.08	0.05	0.69	2	2
Cr^{6+}	0.011	0.008	0.021	0.012	0.06	0.015	0.015	0.013	0.023	0.026	0.011	0.06	0.05	0.05
Mn^{2+}	DL	DL	DL	0.06	DL	0.02	0.20	0.30	0.60	0.10	DL	0.60	0.5	0.4
Total Fe	0.03	0.04	0.02	0.03	0.02	0.05	0.04	0.50	0.03	0.19	0.02	0.50	0.3	0.3

Note: Turbidity in NTU, temperature in °C, and the concentrations of other parameters in mg/L.

Abbreviations: ESA: Ethiopian standards agency; NGL: No guideline value; DL: Detection limit; TH: Total hardness; TA: Total alkalinity; TDS: Total dissolved solids; Min: Minimum; Max.: Maximum; WHO: World Health Organization.

parameters—pH, TDS, HCO_3^-, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, NO_3^-, PO_4^{3-}, TH, Cu^{2+}, Fe, and F^-—along with their corresponding WHO standard values (Table 4).[33,34] These parameters were selected based on recommendations from previous studies.[12,16,32,35]

The calculation of the WQI involves four steps, as described by Berhe,[12] Ha *et al.*,[32] and Sanad *et al.*[13]. In the first step, the physicochemical parameters were assigned weights (wi) on a scale of 1 – 5, as presented in Table 4. These weights were determined based on similar studies conducted by Berhe,[12] Sanad *et al*.,[13] Al-Aizari *et al*.,[18] Panneerselvam *et al*.,[19] and Ha *et al*.[32]

In the second step, the relative weight (W_i) for each parameter was calculated using Equation I, as shown in Table 4. The third step involved assigning a quality rating scale (q_i) to each parameter using Equation VI.

$$q_i = \left[\frac{C_i}{S_i}\right] \times 100 \quad \text{(VI)}$$

where Ci represents the experimental concentration of each parameter in each water sample, measured in mg/L, and Si refers to the standard concentration for each water quality parameter in drinking water, as recommended by the WHO,[33,34] also in mg/L.

Finally, the sub-index (SI_i) value for each water quality parameter was calculated using Equation VII, and the WQI for each groundwater source was calculated using Equation VIII. The resulting scores were classified into five water quality categories, as shown in Table 6.

$$SI_i = W_i \times q_i \quad \text{(VIII)}$$

where the SI_i is the sub-index value of i^{th} parameter, q_i is the rating based on the concentration of i^{th} parameter and n is the number of parameters.

$$WQI = \sum_{i=1}^{n} SI_i = \sum_{i=n}^{n} Wiqi \quad \text{(VIII)}$$

where the SI_i is the sub-index value of i^{th} parameter, Wi is the relative weight, q_i is the rating based on the concentration of i^{th} parameter and n is the number of parameters.

2.6. Data analysis

Descriptive statistics, including percentages, means, and ranges, were computed for the physicochemical data of drinking water samples. A Pearson correlation matrix (*r*) analysis was performed to quantify the relationships among the physicochemical parameters and between the physicochemical parameters and the WQI. All data analyses were conducted using Microsoft Excel 2016.

3. Results and discussion

3.1. Physicochemical analysis

The average values of the physicochemical parameters used to assess the quality of groundwater in the study area are presented in Table 5, alongside comparisons with the drinking water quality standards established by the Ethiopian Standards Agency (ESA)[36] and the WHO.[34]

3.1.1. pH

Table 6. Water quality classifications of samples based on the GPI, NPI, and WQI values[12,13,18,32]

Sample site	GPI value	Category	NPI value	Category	WQI value	Category
Y1	0.816	Insignificant pollution	4.04	Very high pollution	88.1	Good
Y2	0.644	Insignificant pollution	1.97	Moderate pollution	72.2	Good
Y3	0.190	Insignificant pollution	−0.89	Clean (unpolluted)	19.4	Excellent
Y4	0.757	Insignificant pollution	1.93	Moderate pollution	71.9	Good
E1	0.458	Insignificant pollution	−0.82	Clean (unpolluted)	45.7	Excellent
E2	0.416	Insignificant pollution	−0.82	Clean (unpolluted)	40.5	Excellent
S1	0.398	Insignificant pollution	−0.78	Clean (unpolluted)	38.9	Excellent
S2	0.406	Insignificant pollution	−0.85	Clean (unpolluted)	41.2	Excellent
D1	1.444	Low pollution	1.95	Moderate pollution	143.6	Poor
D2	1.29	Low pollution	0.85	Low pollution	128.6	Poor

Abbreviations: GPI: Groundwater pollution index; NPI: Nitrate pollution index; WQI: Water quality index.

The mean pH values of the water samples from the study area ranged from 6.25 to 8.11. The majority of the samples (60%, $n = 10$) fell within the recommended pH range of 6.50 – 8.50 as established by the WHO.[34] However, 40% of the samples had pH values below the recommended lower limit of 6.50. Notably, almost all the samples (90%) exhibited acidic pH levels, with the exception of one sample (10%) from the E1 sampling site, which was slightly basic (pH = 8.11) (Table 5).

3.1.2. Turbidity

The turbidity values of the water samples ranged from 0 to 4 NTU. Of the ten samples analyzed, four (40%) had turbidity values >0 NTU. However, all samples remained below the maximum allowable turbidity level of 5 NTU, as recommended by the WHO.[34]

3.1.3. TDS

The water samples analyzed in this study exhibited TDS concentrations ranging from 99.0 to 1930.0 mg/L (Table 5). Notably, except for two samples (20% of the total, $n = 10$) collected from the D1 and D2 sampling sites, all other samples had TDS concentrations below the public acceptability threshold of 1000 mg/L recommended by the WHO.[34] Based on these TDS values and the palatability ratings for drinking water provided by the WHO,[37] the groundwater sources in the study area were categorized as follows: Two sources (20%) (Y3 and S2) were classified as excellent for potable use, while four sources (40%) (Y2, E1, E2, and S1) were rated as good for drinking; two sources (20%) (Y1 and Y4) were considered fair for human consumption, and the remaining two sources (D1 and D2) were classified as unacceptable for human consumption and require close monitoring. The elevated TDS values observed in certain samples, particularly from the D1 and D2 sites, may be attributed to natural interactions between rocks and water sources in the area, as noted by Berhe.[12] This interaction can lead to the dissolution of minerals and the subsequent release of dissolved solids into the water, increasing the TDS concentrations.

3.1.4. TA

The TA concentrations in the water samples ranged from 110 to 360 mg/L (Table 5). The Ethiopian Standards Agency[36] recommends that TA should not exceed 200 mg/L in drinking water. Of the ten water samples analyzed, four (40%) – E1, E2, D1, and D2 sampling sites – had TA values that exceeded this maximum permissible limit. Bicarbonate alkalinity, primarily attributed to HCO_3^- ions, was the dominant form of alkalinity observed in the water samples, as all measured pH values were below 8.3 (Table 5).

3.1.5. Ca^{2+} and Mg^{2+} levels

Elevated levels of Ca^{2+} can lead to abdominal issues and are undesirable for domestic use, as they contribute to encrustation and scaling.[38] The mean concentrations of Mg^{2+} and Ca^{2+} in the water samples were 4.80 – 79.2 mg/L and 22.2 – 284 mg/L, respectively (Table 5). The mean concentrations of Ca^{2+} and Mg^{2+} at the D1 sampling site were 3.79 and 1.58 times higher than the standards set by the ESA[36] and the WHO,[33] which are 75 mg/L and 50 mg/L, respectively. Similarly, at the D2 sampling site, the mean concentrations of Ca^{2+} and Mg^{2+} were 2.93 and 1.49 times higher than the recommended values.

3.1.6. TH

The water samples analyzed showed TH values ranging from 96.00 to 1040.00 mg/L as $CaCO_3$. According to the WHO,[34] the maximum permissible limit for TH in drinking water is 300 mg/L as $CaCO_3$. Sixty percent of the water samples, including those from the Y1, Y2, Y4, E2, D1, and D2 sampling sites, had TH concentrations ranging from 1.05 to 3.47 times higher than the maximum tolerable limit set by the WHO.[34] These sources, therefore, require treatment as they are not suitable for human consumption. In contrast, 40% of the samples, specifically those from the Y3, E1, S1, and S2 sites, met the WHO[34] standards for drinking water TH levels. Based on the laboratory test results and the TH classification method used by the WHO,[33] the investigated groundwater sources were categorized as follows: Seven sources (70%) – Y1, Y2, Y4, E2, S1, D1, and D2 – were classified as very hard water; one source (10%) – Y3 – was classified as moderately hard; and two sources (20%) – E1 and S2 – were classified as hard water. Consequently, all of the investigated groundwater sources in the research area were considered to be hard water. Water hardness is primarily related to the concentrations of Ca^{2+} and Mg^{2+}.[16,39] As a result, all water samples with elevated levels of Ca^{2+} and Mg^{2+} exhibited correspondingly high TH values.

3.1.7. K^+ levels

Increased potassium levels in drinking water, as highlighted by Gintamo *et al.*,[24] can contribute to neurological and digestive issues.

The measured concentrations of K^+ in the water samples ranged from 1.2 to 46.25 mg/L (Table 5). The maximum permissible limits for K^+ in drinking water are 1.5 mg/L and 12 mg/L, according to the ESA[36] and WHO,[34] respectively. Among the ten groundwater sources investigated, only one sample (10%) from the Y3 sampling site had a K^+ concentration (0.9 mg/L) below the maximum permissible limits set by both ESA[36] and WHO.[34] The remaining 90% of the samples had K^+ concentrations that were 2.4 – 30.8 times higher than the standards suggested by the ESA.[36] Except for the sample from the Y3 site, the K^+ concentrations measured in all other samples were higher than those reported in other regions of Ethiopia.[12,40] The elevated K^+ concentrations observed in the water samples from the D1 (46.25 mg/L) and D2 (38.75 mg/L) sampling sites could be attributed to localized chemical weathering of potash feldspars, as noted by Dawit *et al.*[40]

3.1.8. SO_4^{2-} levels

High levels of SO_4^{2-} in drinking water may induce a laxative effect.[25] The measured concentrations of SO_4^{2-} in the water samples ranged from 2.5 to 360 mg/L. Of the ten water samples analyzed, eight (80%) had SO_4^{2-} concentrations within the public acceptability guideline value of 250 mg/L, as recommended by the WHO.[34] However, two samples (20%) from the D1 and D2 sampling sites exceeded this guideline, with concentrations of 360 mg/L and 325 mg/L, respectively. The elevated levels of SO_4^{2-} in the water samples from the D1 and D2 sites may be attributed to the presence of sulfate-containing minerals, such as gypsum or anhydrous calcium sulfate, which can dissolve in water and increase sulfate ion concentrations, as noted by Gebresilasie *et al.*[5] The results for SO_4^{2-}in this study were consistent with the findings of Gebresilasie *et al.*[5] and Abegaz and Midekssa.[41] However, they were inconsistent with the findings of Adamou *et al.*[16]

3.1.9. NO_3^- and NO_2^- levels

Elevated levels of NO_3^- and NO_2^-in drinking water can lead to "blue baby" syndrome (methemoglobinemia).[25,34] The concentrations of NO_3^- in the water samples ranged from 2.2 to 100.8 mg/L (Table 5). The health-based guidelines for NO_3^- in drinking water, as recommended by both the ESA[36] and the WHO,[34] is 50 mg/L. Among the ten water samples analyzed, six (60%) – Y3, S1, S2, E1, E2, and D2 sampling sites – had NO_3^-concentrations that were 0.74 – 22.73 times lower than the health-based guideline values. These findings align with previous studies[5,12,25,39,42,43] conducted in Ethiopia, all of which reported NO_3^-concentrations within the prescribed limit of 50 mg/L.

The recorded NO_2^- concentrations ranged from 0.003 to 0.009 mg/L (Table 5). All tested water samples had NO_2^- concentrations significantly below the health standard value of 3 mg/L, as recommended by both the ESA[36] and the WHO.[34] These findings are consistent with those of Berhe,[12] who reported that NO_2^-concentrations in water from various locations in Kombolcha town, Ethiopia, were within the recommended limits.

3.1.10. F^- levels

The F^- concentrations in the drinking water samples from the present study ranged from 0.32 to 2.52 mg/L, as shown in Table 5. The WHO[34] and the ESA[36] recommend a maximum permissible limit of 1.5 mg/L for F^- in drinking water. Concentrations exceeding this threshold increase the risk of dental fluorosis, and higher levels further elevate the risk of skeletal fluorosis.[44] Nearly 90% (n = 10) of the analyzed water samples had F^- concentrations below the recommended limit of 1.5 mg/L. However, one sample from the E1 sampling site recorded an F^- concentration of 2.52 mg/L, surpassing the limit. Similar studies in Ethiopia by Mengstie *et al.*[43] and Garoma *et al.*[25] reported F^- concentrations in water samples that were consistent with the 90% compliance observed in the present study. In contrast, the results of the present study differ from those of Amanial,[39] who reported F^- concentrations in spring water samples from Arba Minch town, Ethiopia, ranging from 2.048 to 4.415 mg/L, significantly exceeding the standard limit.

3.1.11. Cu^{2+} levels

In the present study, the analyzed water samples exhibited varying concentrations of Cu^{2+}, ranging from 0.05 to 0.69 mg/L (Table 5). Notably, the Cu^{2+} concentrations in these samples were significantly lower, approximately 2.9 – 40 times below the health-based guideline value of 2.0 mg/L, as recommended by both the WHO[34] and the ESA[36] for drinking water. These results are consistent with the findings of Berhe[12] and Lewoyehu,[42] who reported that Cu^{2+} concentrations in water samples from Kombolcha Town and the Mecha District, Ethiopia, were also below the recommended limit.

3.1.12. Cr^{6+} levels

According to the data presented in Table 5, the concentration of Cr^{6+} in the analyzed water samples ranged from 0.01 to 0.06 mg/L. Remarkably, almost all (90%, n = 10) of the water samples exhibited Cr^{6+} concentrations that were 1.92 – 6.25 times lower than the WHO[34] recommended provisional guideline value of 0.05 mg/L for total chromium in drinking water. However, it is important to note that these findings contrast with a study by Gebresilasie *et al.,*[5] which reported that chromium levels in all hand-dug well water samples from Kafta Humera District, Ethiopia, were below the detection limit (DL) of the method used. These differing results underscore the variations in Cr^{6+} concentrations across different geographical locations and water sources.

3.1.13. Mn^{2+} levels

Analysis of water samples revealed that the concentration of Mn^{2+} ranged from the method DL to 0.60 mg/L (Table 5). Of the ten samples examined, five (50%) showed detectable levels of Mn^{2+}. However, the Mn^{2+} concentrations in these samples were significantly lower—from 1.3 to 20 times below the WHO[34] health-based recommended guideline value of 0.4 mg/L for drinking water. Among the samples, only the water collected from the D1 sampling site exhibited an Mn^{2+} concentration of 0.60 mg/L, which exceeded the health-based recommendation value. The Mn^{2+} concentrations measured in this study were lower compared to those reported by Garoma *et al.*[25] but higher than those reported by Gebresilasie *et al.*[5] in Ethiopia.

3.1.14. Total Fe

The water samples examined in this study showed total Fe concentrations ranging from 0.02 to 0.50 mg/L. Among the ten samples analyzed, only one (S2 sampling site) exhibited a total iron concentration of 0.50 mg/L, exceeding the WHO[34] recommended taste threshold for iron in drinking water, which is set at 0.3 mg/L. The total iron concentrations observed in this study were lower compared to findings from various regions in Ethiopia, as reported by Shigut *et al.,*[45] Gebresilasie *et al.*[5], and Lewoyehu.[42] The variations in iron levels may be attributed to factors such as geological characteristics, water sources, agricultural practices, and other local influences on water quality.

3.2. GPI

According to Sanad *et al.,*[13] the GPI is used as a comprehensive metric that accounts for the combined effects of various chemical factors on groundwater quality, offering a single value that reflects the overall level of groundwater pollution.

The GPI value effectively reflects the degree of groundwater contamination.[18] The GPI values classify water quality into the following categories: "Insignificant pollution" (GPI < 1), "Low pollution" (1 < GPI < 1.5), "Moderate pollution" (1.5 < GPI < 2.0), "High pollution" (2.0 < GPI < 2.5), and "Very high pollution" (GPI > 2.5), as outlined by Sanad *et al.*[13] The calculated GPI values, presented in Table 6, ranged from 0.190 to 1.44, categorizing the water quality into two distinct groups: "Insignificant pollution" and "Low pollution". The results showed that 80% of the 10 ground drinking water sources investigated (Y1, Y2, Y3, Y4, E1, E2, S1, and S2) were in the "Insignificant pollution" category, indicating excellent suitability for drinking. In contrast, 20% of the sources, specifically D1 and D2, were classified as having "Low pollution". Notably, the highest GPI value of 1.44 was recorded at D1 (Table 6).

3.3. NPI

In this study, NPI values ranged from −0.89 to 4.04, with an average of 0.658. The NPI is a tool used to assess water pollution caused by elevated nitrate concentrations.[46] The NPI values classify water quality as follows: "Clean (unpolluted)" (NPI < 0.0), "Low pollution" (0.0 < NPI < 1.0), "Moderate pollution" (1.0 < NPI < 2.0), "High pollution" (2.0 < NPI < 3.0), and "Very high pollution" (NPI > 3.0), as outlined by Al-Aizari *et al.*[18] Analysis of the NPI values (Table 6) reveals that samples from sites Y2, Y4, and D1 exhibited values of 1.97, 1.93, and 1.95, respectively, categorizing them as experiencing Moderate Pollution, which accounts for 30% of the total samples. Five sites (Y3, E1, E2, S1, and S2), representing 50% of the total, were classified as "Clean (unpolluted)". The D2 site was categorized as having "Low pollution". Notably, the Y1 site was classified as experiencing "Very high pollution", indicating a significant and concerning level of nitrate contamination at this location.

3.4. WQI

The WQI offers a detailed assessment of the quality of surface and groundwater for a wide range of domestic uses.[47] As a rule, the WQI is utilized to appraise the suitability of groundwater for drinking purposes in accordance with established the WHO standards.[13]

The WQI values are classified as follows: "Unsuitable for drinking" (WQI ≥300), "Very poor" (200 < WQI < 300), "Poor" (100 < WQI < 200), "Good" (50 < WQI < 100), and "Excellent" (WQI < 50). These classifications are based on the work of Elssaidi *et al.*[3] Table 6 presents the WQI values for all groundwater samples analyzed, as calculated using Equations I, VI, VII, and VIII. The WQI values, as shown in Table 6, ranged from 19.4 to 143.6 across the 10 sampling sites, with an average value

Table 7. Correlation matrix among the various water quality parameters

Parameter	T	Turbidity	EC	TDS	pH	HCO_3^-	TA	K^+	Mg^{2+}	Ca^{2+}	TH	SO_4^{2-}	NO_3^-	Cr^{6+}	Total Fe	WQI
T	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	0.265	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EC	0.526	0.470	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-
TDS	0.526	0.471	**1**	**1**	-	-	-	-	-	-	-	-	-	-	-	-
pH	0.239	0.159	0.195	0.195	**1**	-	-	-	-	-	-	-	-	-	-	-
HCO_3^-	0.419	0.246	**0.720**	**0.720**	0.084	**1**	-	-	-	-	-	-	-	-	-	-
TA	0.419	0.246	**0.720**	**0.720**	0.084	**1**	**1**	-	-	-	-	-	-	-	-	-
K^+	**0.699**	0.287	**0.945**	**0.945**	−0.170	**0.814**	**0.815**	**1**	-	-	-	-	-	-	-	-
Mg^{2+}	0.353	0.374	**0.866**	**0.866**	−0.360	**0.652**	**0.652**	**0.836**	**1**	-	-	-	-	-	-	-
Ca^{2+}	0.446	0.551	**0.956**	**0.956**	−0.270	0.566	0.566	**0.834**	**0.776**	**1**	-	-	-	-	-	-
TH	0.448	0.510	**0.976**	**0.976**	−0.310	**0.666**	**0.666**	**0.892**	**0.912**	**0.962**	**1**	-	-	-	-	-
SO_4^{2-}	0.470	0.541	**0.961**	**0.961**	−0.240	0.580	0.580	**0.851**	**0.806**	**0.969**	**0.963**	**1**	-	-	-	-
NO_3^-	0.120	0.573	0.504	0.504	−0.170	−0.050	−0.050	0.214	0.376	**0.670**	0.569	**0.681**	**1**	-	-	-
Cr^{6+}	0.042	0.217	0.044	0.044	**0.801**	0.425	0.425	0.168	−0.090	0.159	−0.120	−0.090	−0.370	**1**	-	-
Total Fe	0.478	**0.766**	0.128	0.128	−0.350	−0.060	0.062	0.011	0.036	0.185	−0.080	−0.120	−0.280	−0.160	**1**	-
WQI	0.452	0.447	**0.972**	**0.972**	−0.200	0.621	0.621	**0.865**	**0.850**	**0.964**	**0.975**	**0.981**	**0.651**	0.026	0.026	**1**

Note: The coefficients in bold indicate a statistically significant positive correlation at the 0.05 level (two-tailed).
Abbreviations: EC: Electrical conductivity; T: Temperature; TH: Total hardness; TA: Total alkalinity; TDS: Total dissolved solids; WQI: Water quality index.

of 69.01. Based on the calculated WQI values (Table 6), the groundwater sources investigated were classified into three categories for drinking purposes: "Excellent", "Good", and "Poor". Accordingly, 20% of the Dubuluk (D1 and D2) groundwater samples were rated as "Poor" quality for intended human consumption. On the contrary, 30% of the Yabello (Y1, Y2, and Y4) sampling sites were found to have "Good" water quality. Conversely, 50% of the water samples collected from the present study, namely, those fetched from Yabello (Y3), Elewaye (E1 and E2), and Surupa (S1 and S2), exhibited "Excellent" water quality for human consumption. Notably, none of the water samples analyzed in this study were classified as "Very poor" or "Unsuitable for drinking" based on the WQI values. In a related study conducted in the Kombolcha town area of Ethiopia by Berhe,[12] the WQI values for groundwater samples ranged from 23.47 to 81.22, with an average of 42.14. Based on these values, the groundwater was categorized into two groups: excellent water and good water for drinking. In addition, findings by Mengstie *et al.*[43] indicated that WQI analysis classified the water samples from the source, reservoir, and taps in Hawassa town, Ethiopia, as being of good quality for drinking purposes.

3.5. Correlation coefficient matrix analysis

As reported by Sanad *et al.*,[13] a correlation coefficient (r) close to +1 or −1 indicates a strong positive or negative correlation, respectively, between two variables.

The results of the Pearson correlation matrix (r), obtained from the statistical analysis of 20 selected variables, are presented in Table 7, with bolded coefficients indicating very strong correlations.

In this study, the water temperature showed a significant positive correlation only with K^+ ($r = 0.699$). Meanwhile, turbidity exhibited a significant positive correlation only with total Fe ($r = 0.766$). In addition, TDS and EC demonstrated a perfect positive correlation ($r = 1$). It is important to note that TDS and EC are closely related and can often be used interchangeably.[16]

Variations in TDS as a function of HCO_3^-, TA, K^+, Mg^{2+}, Ca^{2+}, TH, SO_4^{2-}, and the WQI exhibited strong positive associations, with r values ranging from 0.720 to 0.976. The pH of the water samples showed a positive significant correlation only with Cr^{6+} ($r = 0.801$).

Furthermore, HCO_3^- demonstrated significant positive correlations with several parameters, including K^+ ($r = 0.814$), Mg^{2+} ($r = 0.652$), TH ($r = 0.666$), EC ($r = 0.720$), and TDS ($r = 0.720$). TA showed a perfect positive correlation with HCO_3^- levels ($r = 1$). TH displayed a strong positive correlation with HCO_3^- ($r = 0.666$), EC ($r = 0.976$), TDS ($r = 0.976$), K^+ ($r = 0.892$), Mg^{2+} ($r = 0.912$), Ca^{2+} ($r = 0.962$), SO_4^{2-} ($r = 0.963$), and WQI ($r = 0.975$). These correlations indicate the mineralization of the investigated water samples. The results were also consistent with the findings of Adamou *et al.*[16] Strong correlations were observed between Mg^{2+} ($r = 0.912$), Ca^{2+} ($r = 0.962$), and SO_4^{2-} ($r = 0.963$), suggesting that the water samples exhibit permanent hardness, likely caused by the presence of magnesium and calcium sulfates. The WQI of the water samples exhibited significant positive correlations with several parameters, including NO_3^- ($r = 0.651$), EC ($r = 0.972$), TDS ($r = 0.972$), K^+ ($r = 0.865$), Mg^{2+} ($r = 0.8502$), Ca^{2+} ($r = 0.964$), TH ($r = 0.975$), and SO_4^{2-} ($r = 0.981$), indicating their influence on overall water quality.

4. Conclusion

This study aimed to assess groundwater quality for drinking using indices such as GPI, NPI, and WQI. All groundwater samples analyzed exhibited turbidity, pH, HCO_3^-, NO_2^-, and Cu^{2+} concentrations within or below the threshold values set by the WHO. However, some parameters exceeded the recommended limits. All groundwater sources investigated were classified as hard water.

The GPI values ranged from 0.190 to 1.44, with the majority (80%) of the ground drinking water sources categorized as "Insignificant pollution" (GPI < 1), indicating their suitability for human consumption. In contrast, 20% of the sources were classified as having "Low pollution" (1 < GPI < 1.5). The NPI values ranged from −0.89 to 4.04, with 50% of the groundwater drinking source classified as "Clean (unpolluted)". Three sources (30%) were classified as experiencing "Moderate pollution". The D2 groundwater drinking source was categorized as "Low pollution". Notably, the Y1 groundwater drinking source was identified as experiencing "Very high pollution", indicating a significant and concerning level of nitrate contamination likely linked to anthropogenic activities, such as fertilizer use and sewage intrusion. The WQI analysis revealed that 50% of the groundwater sources are classified as "Excellent" quality for drinking, while 30% are rated as "Very good" and 20% as "Good" quality for human consumption. The findings of this study provide valuable insights for policymakers and relevant authorities, supporting informed decision-making and effective management strategies.

Acknowledgments

The authors wish to express their sincere gratitude to the Oromia Regional State Water and Energy Bureau for granting access to its water quality control laboratory and providing the necessary chemicals and facilities, which were crucial for conducting the Chemical water quality tests.

Funding

None.

Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Conceptualization: All authors
Investigation: Dereje Diriba
Methodology: Dereje Diriba
Writing – original draft: Dereje Diriba
Writing – review & editing: All authors

Availability of data

Data are available from the corresponding author upon reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 115-121.
doi: 10.36922/ajwep.7526

ORIGINAL RESEARCH ARTICLE

Saturated hydraulic conductivity of soils in the presence of vermicast: Effects of soil texture and vermicast sizes

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Received: December 13, 2024; 1st revised: February 23, 2025; 2nd revised: February 26, 2025; Accepted: March 3, 2025; Published Online: March 19, 2025

Abstract: The present experiment was conducted to observe the effects of different size fractions of vermicast on the saturated hydraulic conductivity (*Ks*) of loam and sandy loam soils. To set up the experiment, loam and sandy loam soils were incorporated with vermicast of different sizes as raw, 1.0 – 2.0 mm, 0.5 – 1.0 mm, and <0.5 mm, at 0, 5 t/ha, 10 t/ha, 15 t/ha, and 20 t/ha, which resulted in five different treatments for each soil type. The *Ks* was determined based on the principle of Darcy's Law by maintaining a constant water head on the top of the soil column. Results indicated that sandy loam soils had significantly higher *Ks* than loam soil for all the application rates ($p < 0.01$). Irrespective of the size, the applications of vermicast at the rates of 5 t/ha, 10 t/ha, 15 t/ha, and 20 t/ha resulted in 113.67 – 196.79%, 135.47 – 442.76%, 10.0 – 150.0%, and 29.63 – 135.47% higher *Ks* in sandy loam soils relative to the loam soils. There were significant differences in *Ks* among the vermicast sizes at all the rates of incorporation for both loam and sandy loam soil treatments ($p < 0.01$). As the size of vermicast decreases (<0.5 mm), the *Ks* also decreases relative to the control, indicating the greater retention capacity and water-holding capacity of finer vermicast fractions in the soil column. At 15 t/ha and 20 t/ha, the highest relative *Ks* (74.42% and 88.37%) were found in loam soils with raw vermicast.

Keywords: Saturated hydraulic conductivity; Loam soils; Sandy loam soils; Vermicast sizes

1. Introduction

Environmentalists and soil scientists find it difficult to maintain soil health to achieve sustainable food production while minimizing environmental pollution. The most important method for improving the physical, chemical, and biological characteristics of soils is the application of organic manure.[1-5] Various organic resources, including kitchen trash, cattle manure, and poultry manure, have been examined and proven to be successful in boosting agricultural yields, strengthening soil fertility, and improving soil conditions.[6,7] Vermicomposting, the technique of composting organic materials with earthworm assistance, has gained a lot of popularity recently. Vermicompost is an effective, economical, environmentally safe, and sustainable organic fertilizer that is made by employing epigeic earthworms to compost a range of organic materials.[8,9] Vermicompost enhances the chemical and physical properties of soil, including cation exchange capacity, organic carbon content, availability of plant nutrients, soil porosity, water retention capacity, soil structure, infiltration rate, and erosion resistance.[2,10-13]

The key soil characteristics that either directly or indirectly influence other soil behaviors are the hydraulic properties. Predicting the soil–plant–water relationship, water infiltration and storage, irrigation and drainage, nutrient and pollutant leaching, runoff and catchment management, and the potentiality of soils with regard to productivity all depend on the saturated hydraulic conductivity (*Ks*) of the soil.[2,14,15] The *Ks* is influenced by soil properties, soil depth, vegetation types, management practices, and so on.[16-19] Among the physical indices, the saturated *Ks* change with soil texture, geometry of soil particles, porosity, and bulk density.[20,21] It is noteworthy that different management approaches and the incorporation of organic amendments have been shown to affect the saturated *Ks* of soils.[2,22,23] However, the saturated hydraulic conductivity and other hydraulic properties of soils seem to be significantly impacted by the variability of particle size distributions. Both the distribution of soil particle sizes or soil texture and the spatial arrangement of these particles or soil structure affect the *Ks* values.[24]

At present, there is a paucity of knowledge regarding the link between vermicast size and *Ks*. Although the effects of soil texture and types of organic manure on *Ks* of soils have been studied separately, to the best of the author's knowledge, none of the previous research manifests the effects of vermicast size on the *Ks*, and how cast sizes affect conductivity in different textural classes of soils. Therefore, this study investigates the impact of adding different size fractions of vermicast on the *Ks* of two distinct soil types and clearly illustrates how the various vermicast sizes affect the saturated hydraulic conductivity.

2. Materials and methods

The soil samples for this investigation were collected from two distinct, undisturbed locations on the campus of Chittagong University that differed widely in terms of soil texture. From the field next to Ansar camp (22°27'56" N 91°46'46" E), loamy soil was collected, and sandy loam soil was taken from the soil science department's experimental field (22°27'58" N 91°46'49" E) of the Chittagong University. Samples of soil were taken between 0 and 15 cm below the surface. Following collection, samples were broken through gentle crushing with a wooden hammer and allowed to air dry. The samples of soil were then passed through a 2 mm stainless steel sieve. The sieved samples were kept for the purpose of analyzing the soil's chemical and physical characteristics.[25,26] Bulk vermicompost was collected from an organic farm, air-dried, and sieved to separate into different size fractions, namely, raw, 1.0 – 2.0 mm, 0.5 – 1.0 mm, and <0.5 mm. Figure 1 shows different size fractions of vermicast used for this experiment.

To set up the experiment, 100 g (on oven dry weight basis) of 2 mm sieved soil samples were weighed. Then, the required amount of vermicast of different size ranges for the rates of 5 t/ha, 10 t/ha, 15 t/ha, and 20 t/ha were weighed and thoroughly mixed with the previously weighed soil samples. The incorporation of vermicast resulted in five different treatments for each soil type. The treatment arrangement comprising different sizes of vermicast is shown in Table 1. For every experimental condition, we compared the results and treatments with a control setup and performed a reasonable number of replications (Table 1).

After mixing up the soil and vermicast of different sizes independently, the samples were packed in the aluminum core (4 cm in height and 5.6 cm in diameter), maintaining a roughly uniform bulk density. Amended and controlled soils inside the cores were initially subjected to wetting from the bottom. After complete saturation, distilled water was passed through the soil-filled cores. By maintaining a constant water load, the *Ks* were determined by measuring the volume of water passing through the soil column. The amount of water passed through the soil column was measured using a measuring cylinder, and the data were recorded to calculate *Ks*.[25] The *Ks* of both soils was calculated using the following formula:

Figure 1. Different size fractions of vermicast

Table 1. Treatment arrangement with different types of vermicast

No.	Treatments (Loam and sandy loam soils)
1.	Control (Soil without vermicast)
2.	Soil+vermicast (Raw)
3.	Soil+vermicast (1.0 – 2.0 mm)
4.	Soil+vermicast (0.5 – 1.0 mm)
5.	Soil+vermicast (<0.5 mm)

$$Q = Ks\frac{H_1 - H_2}{L} \quad \text{(I)}$$

$$Q = \frac{V}{At} = \frac{V}{\pi r^2 t} \quad \text{(II)}$$

$$K_s = \frac{VL * 60}{\pi r^2 t(H_1 - H_2)} \quad \text{(III)}$$

where,
K_s = Saturated hydraulic conductivity (cm/h);
Q = flux of the water (cm/h);
V = Volume of water (mL);
L = Height of soil column (cm);
R = Radius of the core (cm);
T = Time (min);
H_1 = Constant water head (cm);
H_2 = Gravitational head (cm).

Before setting up the experiment, the soils were analyzed for physicochemical assay. The pH was measured with a pH meter after preparing the suspension at a 1:5 soil-to-water ratio (w/v).[27] The percentage of sand, silt, and clay was measured by the hydrometer method as described in a paper by Huq and Alam,[26] and the textural class was determined from Marshall's triangular coordinates. The amount of organic carbon in soils was determined by the Walkley and Black wet oxidation method, and the amount of organic matter was estimated indirectly by multiplying the organic carbon content by the van Bemmelen factor of 1.724.[28] Soil-1 and soil-2 were loam and sandy loam in texture, respectively (Table 2). All the statistical analyses were performed using SPSS 16 software (SPSS Inc. Version 16.0. Chicago). One-way analysis of variance was performed to compare among the treatments for 5 t/ha, 10 t/ha, 15 t/ha, and 20 t/ha rates of loam and sandy loam soils and the difference between loam and sandy loam soils for different rates was performed through a paired-sample *t*-test.

Table 2. Physico-chemical properties of experimental soils

Parameters	Soil-1	Soil-2
pH	5.28	5.18
Organic matter (%)	1.87	1.32
Sand (%)	44	62
Silt (%)	36	23
Clay (%)	21	16
Texture	Loam	Sandy loam

3. Results and discussion

3.1. Effect of soil texture on *Ks* in the presence of vermicast

Figure 2 shows the *Ks* of loam and sandy loam soils treated with different rates of vermicast incorporation. Sandy loam soils had significantly higher *Ks* than loam soils' for all the application rates ($p < 0.01$). Irrespective of the size, the applications of vermicast at the rates of 5 t/ha, 10 t/ha, 15 t/ha, and 20 t/ha resulted in 113.67 – 196.79%, 135.47 – 442.76%, 10.0 – 150.0%, and 29.63 – 135.47% higher *Ks* in the sandy loam soils relative to the loam soils. The lower *K*s of loam soils, irrespective of the size of the vermicast could be ascribed to higher clay content and lower sand content in loam soils compared to sandy loam soils. The filling of large soil pores with fine organic materials leads to reduced *Ks*.[29] Pulat *et al.*[30] reported that the application of 1% biopolymer solution to a 70% sand-containing soil sample resulted in a 25-fold decrease in hydraulic conductivity. García-Gutiérrez *et al.*[24] stated that the *Ks* is subjected to particle size and changes with the distribution of soil particles. Sari[19] found a significant negative relationship of *Ks* with that of clay, while a significant positive relationship with that of the sand particles. The bulk density of soil is another determinant that influences the *Ks*, with higher *Ks* with a decrease in the bulk density of soils[31]. However, in our study, bulk density could have very little effect on *Ks* as a uniform bulk density of both soil types was maintained. Under natural conditions, however, the change in bulk density modifies the distribution of soil pores, affecting the ability of soils to conduct water.[32] The differences in *Ks* between loam and sandy loam soils treated with vermicast could be due to differences in geometry between sand and silt particles, and the larger-size strong aggregates formed in the presence of vermicast induce large pore size distribution to facilitate the transport of more water. The geometry of the soil particles determines the size

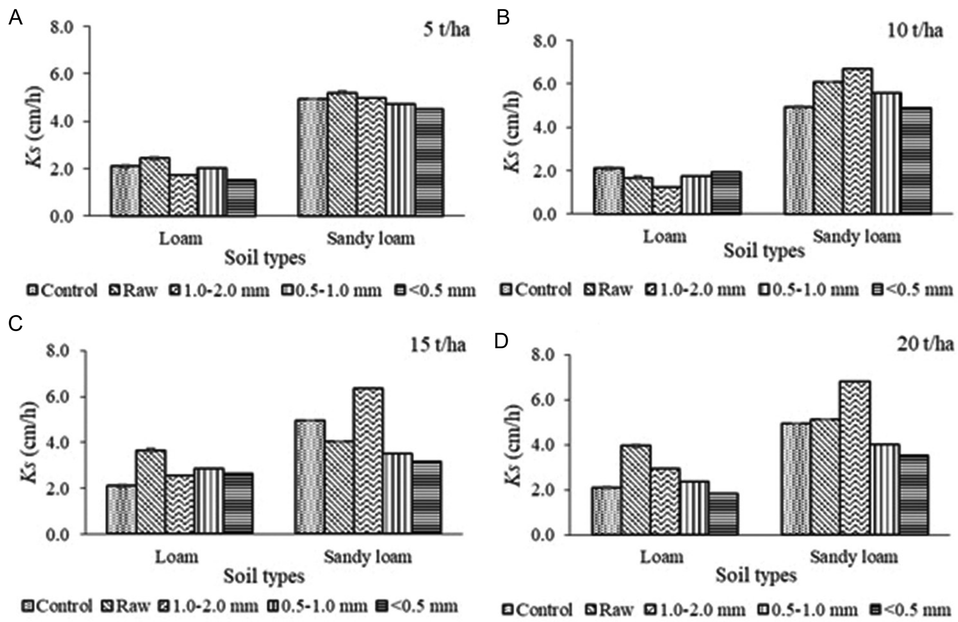

Figure 2. The *K*s of loam and sandy loam soils at different rates of vermicast incorporation: 5 t/ha (A), 10 t/ha (B), 15 t/ha (C), and 20 t/ha (D)

and shape of the pore space affecting the water-holding capacity and flow of water.[21,33]

3.2. Effect of vermicast sizes on *Ks* in loam and sandy soils

The relative *Ks* of loam and sandy loam soils are shown in Figure 3. There are significant differences in the *Ks* among the vermicast-amended loam and sandy loam soils ($p < 0.01$). As for loam soils, 5 t/ha, 15 t/ha, and 20 t/ha applications of raw vermicompost resulted in 60.43%, 74.42%, and 113.16% higher *Ks*, respectively, compared to the corresponding lowest values. This increase of *Ks* with the addition of vermicast is comparable with the findings of Hemdan *et al*.[22] In a pot experiment, Hemdan *et al.*[22] found that incorporating vermicast into agricultural loamy clay soils increased their hydraulic conductivity by 61.47%. In the case of 5 t/ha in sandy loam soils, the maximum *Ks* was observed due to the application of a raw cast, followed by a cast with a size of 1.0 – 2.0 mm. As for 10 t/ha, 15 t/ha, and 20 t/ha applications of different types of vermicast in sandy loam soils, the highest *Ks* were found when soils were treated with vermicast in a size range of 1.0 – 2.0 mm.

On the other hand, the lowest *Ks* was observed in sandy loam soils treated with <0.5 mm-sized vermicast at all the different application rates. The incorporation of 1.0 – 2.0 mm sized vermicast caused 37.50%, 100.0%, and 93.10% higher *Ks* compared to the respective lowest values at the 10 t/ha, 15 t/ha, and 20 t/ha application rates, respectively. The initial high organic matter content in loam soils induces more binding, and the formation of large-size particles increases the large-size pore distribution, which could be another reason for higher *Ks*. Applying compost, rice straw, and sawdust to clay loam-textured soil improved the soil's pore size, hydraulic conductivity, and water-holding capacity, according to Eusufzai and Fujii.[34]

Çal and Barik[16] reported that the soil *Ks* was positively correlated with soil organic matter. However, Sari[19] observed an insignificant positive relationship between hydraulic conductivity and organic matter. At a low rate of incorporation (5 t/ha), the *Ks* decreased in almost all the treated soils compared to the control except for raw vermicast. This could be due to the greater role of vermicast on water retention than water flow at low rates of incorporation. Bhanwaria *et al*.[10] also observed a significant increase in water retention by vermicompost at an even lower rate of incorporation (5 t/ha). Incorporating the raw cast at 5 t/ha resulted in a 16.28% and 5.51% increase in *Ks* relative to control.

As the size of vermicast decreased (<0.5 mm), the *Ks* generally reduced relative to control in sandy loam soils. The lower *Ks* due to the addition of fine-sized cast could be ascribed to the presence of a greater surface area by which hydrated counterions were absorbed.[35] A similar scenario was observed for loam soils, except for those with 15 t/ha incorporation. Yılmaz and Alagöz[36]

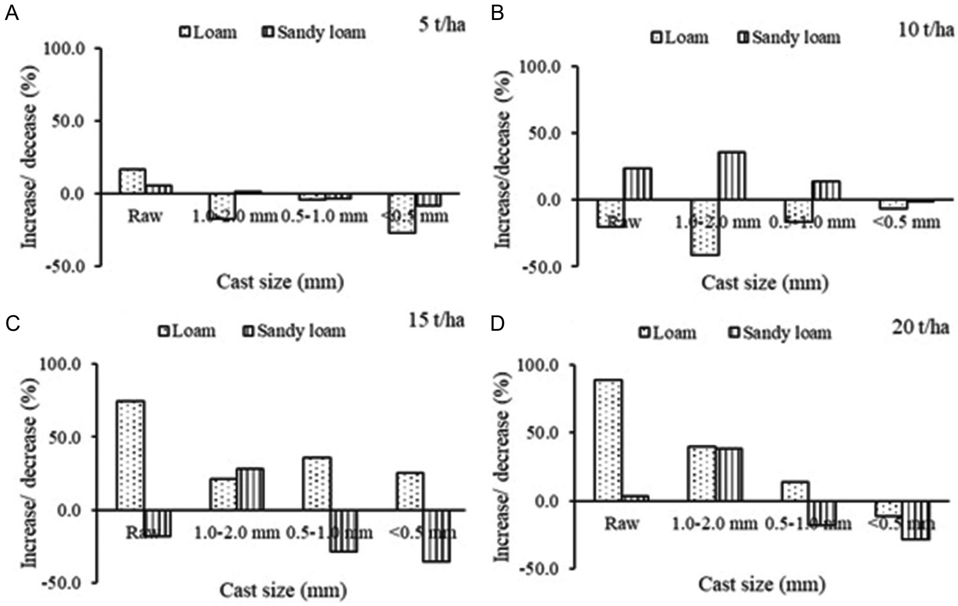

Figure 3. Relative increase and decrease in *K*s of loam and sandy loam soils: 5 t/ha (A), 10 t/ha (B), 15 t/ha (C), and 20 t/ha (D)

found that the moisture retention capacity of soil is influenced by the size of the organic matter. Demir and Doğan[2] and Liu *et al*.[37] also reported that the *Ks* of soil are influenced by the amount and types of organic materials. However, maximum relative *Ks* in loam soils incorporated with raw vermicast was found when the incorporation rates were set at 15 t/ha and 20 t/ha, consistent with the findings of Yılmaz and Alagöz[36] that the water-holding capacity of soils increased as the organic materials in soils increased. Relative to control, 15 t/ha and 20 t/ha of raw cast incorporation resulted in 74.42% and 88.37% higher *Ks*, respectively. The phenomenon behind greater *Ks* due to adding raw cast at higher doses could be attributed to the high number of residual pores facilitating a greater water flow by gravity.

4. Conclusion

The *Ks* of soils determine the water holding capacity, infiltration rate, accessibility of plants for water intake, and the movement of nutrients and pollutants in soil, thereby determining the capability of the soils to serve the ecosystem. As the incorporation of vermicompost into the soil is one of the most significant approaches to improving soil's physical, chemical, and biological conditions, it is of utmost importance to evaluate the effect of appropriate size fractions of vermicast on such soil physical properties like *Ks*. This experiment effectively illustrates the substantial influence of vermicast size fractions and textural classes on the saturated hydraulic conductivity of soils by utilizing only two textural classes and four distinct vermicast fractions, thereby providing insights into addressing the limitations of sample variations in this investigation. This study also deduced that the raw and the largest size fractions of vermicast increase the *K*s at relatively higher doses regardless of the dose applied. This finding will play an important role in paving the way for future research on the movement and storage of water and the transfer and control of nutrient elements using different-sized fractions of vermicast, especially the application and dose/response relation of nanofertilizers. The results of this investigation clearly indicate that marginal farmers should utilize specific vermicast size fractions while avoiding excessive applications of very costly organic fertilizers. The ultimate purpose of adopting this approach should be based on the water-holding capacity and organic matter content of soils, necessitating planning for the application and treatment of site-specific vermicast and organic fertilizer.

Acknowledgments

The authors acknowledge the laboratory support of the Department of Soil Science, University of Chittagong.

Funding

None.

Conflict of interest

The authors declare that they have no known competing financial interests.

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Availability of data

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 122-133.
doi: 10.36922/AJWEP025050030

ORIGINAL RESEARCH ARTICLE

Efficient energy management in microgrid using Zebra Optimization Algorithm

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(This article belongs to the *Special Issue: Renewable Energy Systems and Strategies in Smart Grids and Smart Cities Development*)

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Received: February 1, 2025; Revised: February 28, 2025; Accepted: February 28, 2025; Published Online: March 20, 2025

Abstract: The inherent variability of power output from photovoltaic (PV) systems, wind energy resources, battery energy storage systems (BESS), and hydrogen (H_2) fuel cells presents a significant challenge in efficiently integrating these technologies into microgrids. This stochastic nature underscores the necessity of accounting for fluctuations in renewable energy resources (RERs) to optimize energy utilization within the microgrid. This paper proposes a resource-efficient energy management (REEM) framework for a microgrid interconnected with the main power system. By dynamically regulating PV generation, wind power output, BESS discharge, and hydrogen fuel cell operation in response to load variations, the proposed approach enhances energy utilization and grid stability. To address the complexities associated with REEM, this study employs the zebra optimization algorithm (ZOA), a highly efficient metaheuristic technique. The primary objectives of this optimization include cost minimization, voltage profile enhancement, and optimal sizing of RERs. Simulation results demonstrate that the strategic integration of PV units, wind turbines, grid-connected BESS, and hydrogen fuel cells significantly reduces operational costs while improving overall system performance. Comparative analysis further reveals that ZOA outperforms the moth-flame optimization algorithm and stochastic fractal search network in achieving the defined optimization objectives.

Keywords: Energy resources; Photovoltaic system; Wind energy; Zebra Optimization Algorithm; Voltage stability; Cost function

1. Introduction

The incorporation of a wide variety of renewable energy sources and the facilitation of power flow in both directions are two of the most important contributions that alternating current (AC) microgrids make to the improvement of energy dependability, resilience, and efficiency.[1-3] They provide flexibility in the management of dispersed generation, the reduction of transmission losses, and the support of grid stability, which ultimately contributes to the promotion of decentralized and sustainable energy systems. Variations in load demand, the unpredictability of renewable energy resources (RERs), the relationship between the grid and the microgrid, and the capacity for energy storage are all factors that influence the functioning of an AC microgrid. Optimal management takes into account these aspects to achieve a balance between supply and demand, guarantee grid stability, and maximize the use of renewable energy sources while simultaneously minimizing costs and the effect on the environment.[4,5]

It is possible to optimize power flow, load scheduling, and resource allocation through the use of AC microgrid energy management (EM). To enhance dependability and lower costs while preserving grid stability, it integrates renewable sources and storage to strike a balance between supply and demand. To guarantee that available resources are used in an efficient manner, intelligent algorithms, and control mechanisms are utilized.[6-8] EM for AC microgrids aims to achieve the following goals: optimize the integration of renewable energy sources, maximize grid stability, minimize operating expenses, and effectively balance supply and demand within the system. To guarantee dependable and environmentally friendly power distribution, it requires real-time monitoring, management, and coordination of generation, storage, and consumption.

AC microgrid EM provides significant improvements in terms of flexibility, dependability, and efficiency when it comes to the integration of various energy sources. In addition to facilitating grid stability and supporting dynamic load control, it promotes the effective use of renewable resources. The design of the AC microgrid also makes it simpler to integrate with the infrastructure that is already in place, which helps to improve grid resilience and scalability. In our study, an optimal EM strategy for AC microgrids is proposed to enhance the integration of renewable energy sources.[9-14]

Through extensive simulations, as demonstrated previously,[15] the proposed strategy achieves a significant reduction in overall system costs while ensuring grid stability. Specifically, the optimization algorithm employed, based on particle swarm optimization, minimizes the total energy procurement expenses and maximizes renewable energy utilization. The results indicate that existing methods in terms of both economic benefits and environmental sustainability. A paper by Dey *et al.*[16] presents an adaptive control scheme tailored for AC microgrid EM, integrating demand response mechanisms and energy storage systems (ESS). The proposed scheme optimally schedules energy generation and consumption considering varying load profiles and renewable energy availability. By employing a modified genetic algorithm for optimization, our approach dynamically adjusts energy dispatch strategies to minimize operational costs and maintain grid stability. Simulation results validate the effectiveness of the proposed scheme in achieving optimal operation of AC microgrids under different operating conditions.[17-19]

Zebra optimization algorithm (ZOA) was employed in this study due to its superior capability in solving complex optimization problems related to EM in microgrids. ZOA is inspired by the collective movement and foraging behavior of zebras, effectively balancing exploration and exploitation in the search space.[20] This characteristic is crucial in microgrid EM, where optimal decisions must be made dynamically to accommodate fluctuations in renewable energy generation and load demand. Unlike conventional optimization techniques, ZOA demonstrates faster convergence rates and avoids local optima more effectively.[21] This is particularly beneficial when optimizing energy dispatch strategies involving multiple RERs, as it enhances the efficiency and stability of the microgrid. Further, the ZOA is well-suited for handling such multi-objective optimization problems.[22]

This work addresses the issues that were described before and presents a method by which ZOA can effectively respond to changing circumstances, hence increasing the resilience of AC microgrids against interruptions and uncertainty. The adaptability of ZOA across microgrids of varying sizes and configurations provides scalability and flexibility, providing answers to a wide variety of problems related to EM. The structure of this paper unfolds as follows: Section 2 elaborates on the problem formulation of the resource-efficient EM (REEM) system. In Section 3, the ZOA system is outlined. Section 4 delves into the simulation results of the proposed ZOA algorithm, comparing its performance with existing algorithms. Finally, Section 5 provides a comprehensive summary of the work conducted in this study.

2. Problem formulation

The management of energy in a microgrid is achieved through the integration of six distinct objective functions within a comprehensive framework that addresses multiple targets. The significant goal is to amplify the utilization of energy while at the same time guaranteeing that microgrid sticks to the furthest reaches that have been set on it.[23,24] The methodology attempts to harmonize a few components of EM by including various goals to accomplish this equilibrium. These viewpoints incorporate effectiveness, trustworthiness, and supportability. Moreover, the convergence of these objectives into the multi-objective capability makes it conceivable to adopt a comprehensive strategy to the streamlining of energy for the microgrid, which thus makes it simpler to meet the limitations of the microgrid and works on the general execution of the framework. The microgrid EM framework is displayed in Figure 1, which shows its setup. The wind turbine (WT) and photovoltaic system (PV) are the portion of the sources that are recommended for the microgrid plan.

2.1. Goal function

2.1.1. Measures for cost-saving

Several components increase the total annual cost of electricity produced by a microgrid. They include the annual energy loss cost (R_{loss}), the expenditure associated

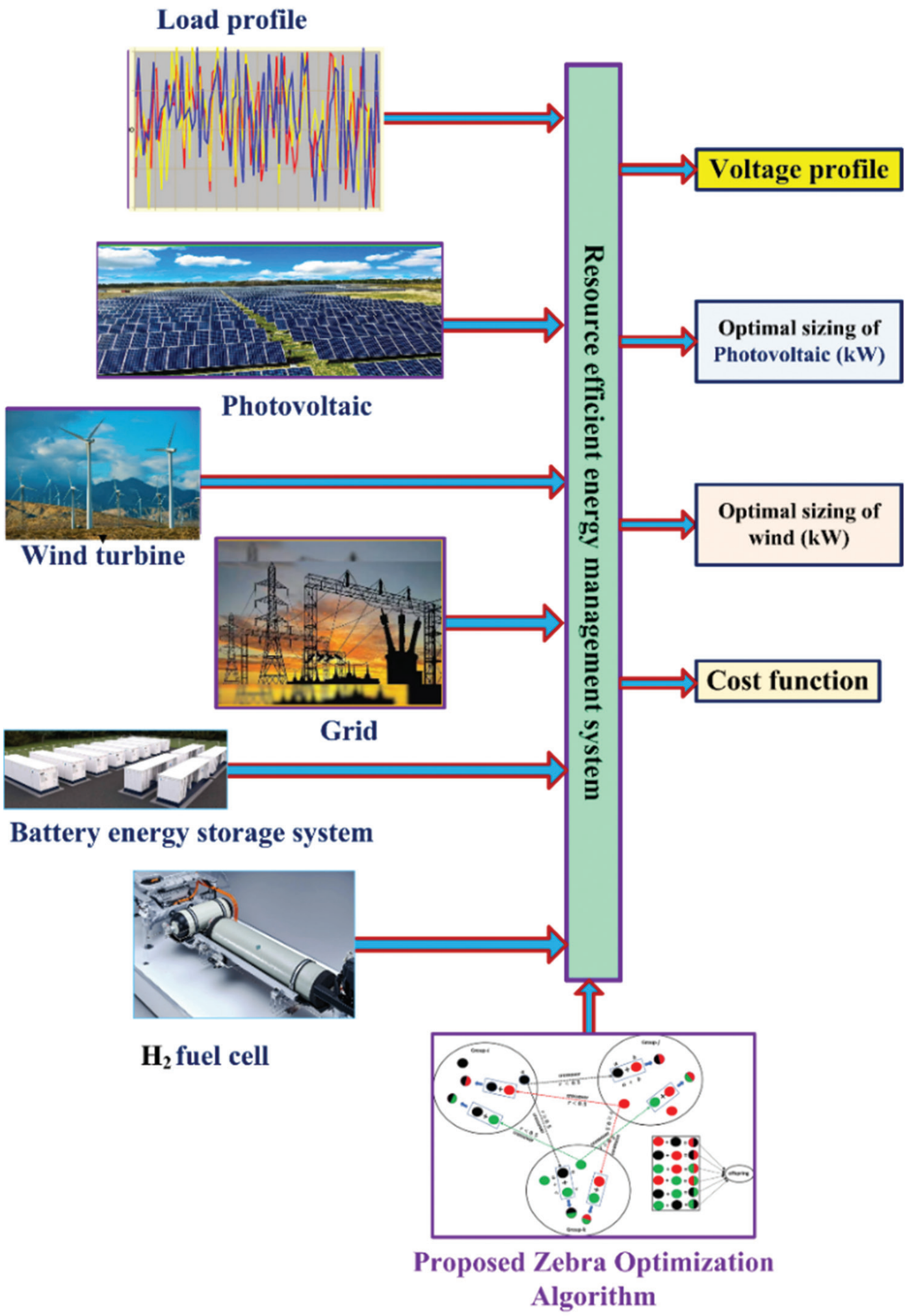

Figure 1. Configuration of microgrid smart energy management system (SEMS)
Abbreviations: BESS: Battery energy storage system; PV: Photovoltaic; ZOA: Zebra Optimization Algorithm.

with transporting electricity from the electric substation (R_{Grid}), the costs of the PV units (R_{PV}), WTs (R_{WT}), battery ESS (BESS) unit (R_{BESS}), and H2 fuel unit (R_{FC}). The above-mentioned components together account for the total cost associated with EM.[25] The total cost function scenarios are expressed by Equation I.

$$R = min\,(R_{loss} + R_{Grid} + R_{PV} + R_{WT} + R_{BESS} + R_{FC}) \qquad \text{(I)}$$

Equation I is rearranged as

$$R_{loss} = 365 \times \delta_{loss} \times \sum_{k=1}^{24} p_{loss}(k) \qquad \text{(II)}$$

$$R_{Grid} = 365 \times \delta_{Grid} \times \sum_{k=1}^{24} p_{Grid}(k) \qquad \text{(III)}$$

$$\left.\begin{aligned} R_{PV} &= R_{PV}^{I} + R_{PV}^{O,M} \\ R_{PV}^{I} &= cf \times \delta_{PV} \times p_{r,PV} \\ R_{PV}^{O,M} &= \delta_{PV}^{O,M} \times \sum_{k=1}^{24} p_{PV}(k) \end{aligned}\right\} \qquad \text{(IV)}$$

$$\left.\begin{aligned} R_{WT} &= R_{WT}^{I} + R_{WT}^{O,M} \\ R_{WT}^{I} &= cf \times \delta_{WT} \times p_{r,WT} \\ R_{WT}^{O,M} &= \delta_{WT}^{O,M} \times \sum_{k=1}^{24} p_{WT}(k) \end{aligned}\right\} \qquad \text{(V)}$$

$$cf = \frac{\psi \times (1+\psi_{PV,WT,DG,B,FC})^{np_{PV,WT,DG,BESS,FC}}}{(1+\psi_{PV,WT,DG,B,FC})^{np_{PV,WT,DG,BESS,FC}} - 1} \qquad \text{(VI)}$$

In Equations I to VI, the cost of obtaining electricity from the grid is represented by δGrid, and the cost of energy loss is represented by δO. The costs for maintaining and operating the PV unit and WTs are indicated by $\delta_{PV}^{O,M}$ and $\delta_{WT}^{O,M}$, respectively. The PV system and WTs installation costs are represented by R_{PV}^{I} and R_{WT}^{I}, respectively, and are expressed in ₹/kW. The $\psi_{PV,\,WT}$ represents the combined installed costs of the PV system and the WTs. $np_{PV,\,WT}$ is the equivalent portion of time that a PV system or WTs operates at full output capacity, and *cf* stands for the capital recovery factor.

2.1.2. Enhancement of voltage profile

The system's performance would be enhanced by the decrease in voltage fluctuations. N is the total number of buses in the grid, and V_n is the voltage of the n-th bus. This is can be achieved by minimizing voltage level variations, which will enhance the system's overall dependability and efficiency.[26]

$$\sum VD = \sum_{k=1}^{24} \sum_{m=1}^{N} \left|(V_n - 1)\right| \qquad \text{(VII)}$$

2.1.3. Voltage stability improvement

The third goal function emphasizes raising the voltage stability index (*vsi*) to its maximum value in order to enhance stability. This index serves as a metric to assess and improve the system's overall voltage stability,[27-29] making it possible for the system to function more dependably and robustly across a range of operating conditions.

Vsi =

$$vsi = |V_i|^4 - 4\left(p_i X_{i,j} - q_i R_{i,j}\right)^2 - 4(p_i X_{i,j} + q_i R_{i,j})|V_i|^2 \qquad \text{(VIII)}$$

$$\sum vsi = \sum_{k=1}^{24} \sum_{m=1}^{N} vsi_m \qquad \text{(IX)}$$

In Equations VIII and IX, the symbol $R_{i,j}$ is the existing resistance of the transmission line between the buses *i* and *j*. The code $X_{i,j}$, indicates the transmission line's reactance between buses *i* and *j*. At bus *i*, injective active power is represented by the symbol p_i. The symbol q_i stands for power injection at bus *i*.

2.2. Constraints of the proposed energy system

2.2.1. Limitations of inequalities

The inequality limitations of the proposed system vary from minimum to maximum of voltage, current, and power. The associated equation for the inequality limitations is given by Equations X to XIII.

$$V_{\min} \text{ ″ } V_{n} \text{ ″ } V_{\max} \qquad \text{(X)}$$

$$p_{sr} + p_{wr} \le \sum_{i=1}^{n} p_{D,i} \qquad \text{(XI)}$$

$$pf_{\min} \text{ ″ } pf \text{ ″ } pf_{\max} \qquad \text{(XII)}$$

$$I_y \le I_{\max,y};\, y = 1,2,3.....T \qquad \text{(XIII)}$$

$$p_s + p_{PV} + p_{WT} = \sum_{i=1}^{T} p_{loss,i} + \sum_{i=1}^{N} P_{D,i} \qquad \text{(XIV)}$$

$$q_s + q_{PV} + q_{WT} = \sum_{i=1}^{T} q_{loss,i} + \sum_{i=1}^{N} q_{D,i} \qquad \text{(XV)}$$

In Equation XV, the p_s and q_s are active and reactive powers, respectively.

3. Proposed ZOA

Flowchart of ZOA algorithm is shown in Figure 2. The ZOA is used primarily to optimize REEM in microgrids. This strategy minimizes costs and reliance on fossil fuels, thereby minimizing greenhouse gas emissions. ZOA does this by dynamically adjusting energy production, distribution, and consumption. To improve the microgrid resilience and scalability across a variety of configurations, ZOA can adapt to changing circumstances. The findings of the simulation suggest that ZOA is more effective than other algorithms already in use, making it a potentially useful answer to a wide range of situations involving EM. The life cycle of American zebras unfolds through five distinct stages. These stages include the formation of random zebra groups, feeding activity among American zebras, breeding behavior, the establishment of group leadership, and the subsequent stage of leadership transition involving the selection of a new leader. The mathematical representation of these stages is defined as Equation XVI.[30]

$$\mathring{Z}_j^{k} = \begin{cases} 2R_1 \sin(2\pi R_2) \times (Z_s^k - Z_j^k) + Z_s^k; ifR_3 < 0.5 \\ \forall i \varepsilon N_k \\ 2R_1 \cos(2\pi R_2) \times (Z_s^k - Z_j^k) + Z_s^k; otherwise \end{cases}$$

$$Z_j^k = \begin{cases} \mathring{Z}_j^{k}; \mathring{f}_j^{k} < f_j^k \\ Z_j^k; otherwise \end{cases}$$

$$R_2 = 1 - t \times (\frac{1}{T})$$

(Stage 1 and Stage 2) (XVI)

$$Z_j^q = Crossover\left(Z_j^a, Z_k^b\right); ifr < pc, j \neq k$$

$$Z_k^q = Crossover\left(Z_j^a, Z_k^c\right); ifr \geq pc, j \neq l$$

$$\forall j, k, l \varepsilon N$$

(Stage 3) (XVII)

$$\mathring{Z}_s^{k} = \begin{cases} 2R_4 \sin(2\pi R_5) \times \left(WR - Z_s^k\right) + WR; ifR_6 < 0.5; \\ 2R_4 \cos(2\pi R_5) \times \left(WR - Z_s^k\right) + WR; otherwise \end{cases}$$

$$Z_s^k = \begin{cases} \mathring{Z}_s^{k}, \mathring{f}_s^{k} < f_s^k \\ Z_s^k; otherwise \end{cases}$$

$$R_5 = 1 - t \times \left(\frac{1}{T}\right)$$

(Stage 4) (XVIII)

$$Z_s^k = \left\{ Z_j^k, ifF(Z_j^k) < F(Z_s^k); \forall j \varepsilon N_k \right.$$

(Stage 5) (XIX)

In the described scenario, Z_S^k and Z_j^k denote the positions of the stallion and the j^{th} zebra within the k^{th} group, respectively. N_k represents the total number of members in the k^{th} group. R_1 is uniformly distributed random values ranging from −2 to 2, influencing the feeding behavior of zebras at various angles around the group leader. R_2 represents an adaptive parameter computed using Equation XVI. R_3 is a random value uniformly distributed between 0 and 1. The functions sin and cos aid in the movement of other members at multiple angles around the family leader. Z_j^k represents the updated position of the j^{th} member during feeding, with F_j^k indicating its corresponding fitness value. Furthermore, Z_j^a represents the position of a baby zebra from the j^{th} group, Z_k^b denotes the position of zebra b from the j^{th} group, Z_l^c represents the position of zebra l from the l^{th} group, and Z_k^q and Z_l^q are the positions of zebras q in the k^{th} and l^{th} groups, respectively. R_4 is a uniformly distributed random number between −2 and 2, while R_5 signifies an adaptive parameter calculated using Equation XIX. R_6 is another uniformly distributed random number ranging from 0 to 1; WR represents the water reserves; Z_s^k denotes the current position of the leading stallion in the j^{th} group, while Z_s^k represents its next position, with F_s^k representing its fitness value.

4. Simulation results

The goal of this paper's proposed ZOA for microgrid REEM is to minimize the capacity of distributed generators powered by PV, WT, BESS, and H_2 fuel cell. The application considers scenarios with and without uncertainty. In this work, a comparison is made between

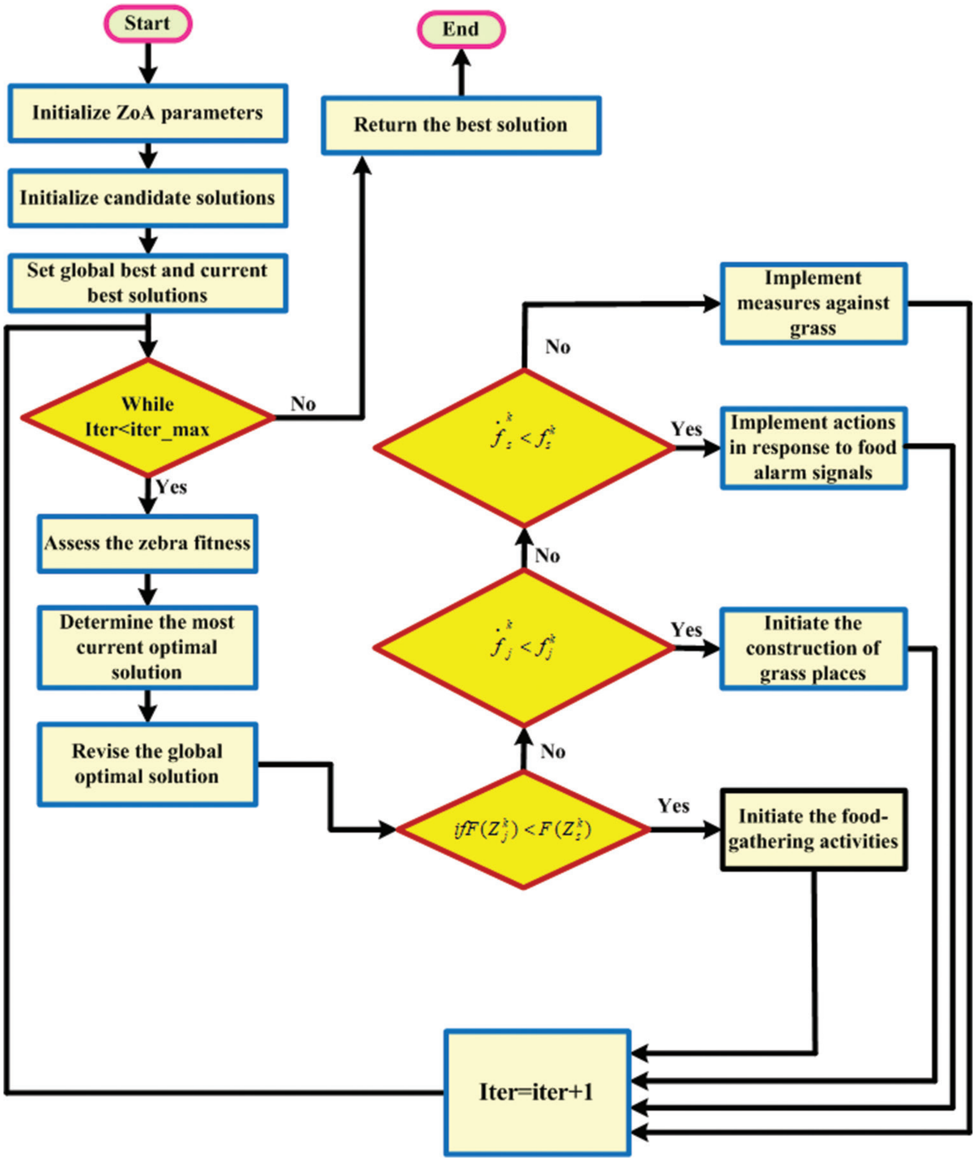

Figure 2. Flowchart of ZoA algorithm

the acquired findings and those from the moth-flame optimization algorithm (MFOA) and stochastic fractal search network (SFSN) to verify the effectiveness of the proposed method. The proposed approach is tested in the IEEE 13 bus system. Table 1 shows parameters for the different algorithms to observe the initial flow of the initial load. Grid specifications are given in Table 2.

4.1. REEM in deterministic conditions

The ZOA solves the REEM problem under deterministic conditions while accounting for input, output, and constraints. An analysis of time-varying market prices, solar irradiance load profile, and wind speed are evaluated for the performance of the proposed algorithm. The various profiles, including the percentage of load, solar irradiance, wind speed, and market price over a 24-h period, are shown in Figure 3A-D, respectively.

Table 1. Selected parameters for the ZOA, MFOA, and SFSN algorithms

Algorithm	Parameters
ZOA	T_{max}=150, R_1=10, R_2=20, R_3=30 and R_4=50
MFOA	T_{max}=150, search agents=20, a_1=2, a_2=2, G.p=0.5
SFSN	T_{max}=150, search agents=50

Abbreviations: MFOA: Moth-flame optimization algorithm; SFSN: Stochastic fractal search network; ZOA: Zebra optimization algorithm.

The voltage profiles with and without RERs are shown in Figure 4, and when the RERs were optimally integrated, the voltage profiles significantly improved.

Table 2. Grid specifications

Specification	Value
Voltage in p.u (minimum)	0.9344
Voltage drop in p.u	0.38
Real load in kW	4
Reactive power in KVAr	3.9
Losses in kW of the grid	20

Table 3. Results of MGs under various conditions

Specification	Without RERs	With RERs
Losses (kWh)	1.45688×10^5	9.8650×10^4
Procurement energy (kWh)	3.45787×10^6	2.9501×10^6
PV unit (kW)	0	386
Optimization size of the WT (kW)	0	60
Overall energy loss cost ($)	8.74149×10^3	5.18867×10^3
Overall cost of procurement energy ($)	3.54878×10^6	2.0951×10^6
Cost PV ($)	0	4.83465×10^4
Cost of wind turbine ($)	0	2.47426×10^4
Total cost ($)	3.5575×10^6	2.17337×10^6

Abbreviations: MGs: Microgrids; PV: Photovoltaic; RERs: Renewable energy resources; WT: Wind turbine.

In terms of the defined objective functions, ZOA outperformed MFOA and SFSN, as shown in Table 3, which contrasts their results. The simulation results displayed in Table 4 were obtained by applying the Evolutionary ZOA, MFOA, and SFSN.

The losses, ideal sizes of the sustainable power sources and purchase cost of energy taken from the grid, and all-out cost are assessed through proposed calculation and with other standard improvement methods like SFSN and MFOA. The outcomes obviously show that the proposed ZOA calculation outperformed in all previously mentioned angles in any events when RERs were not thought of. Without integrating the environmentally friendly power assets, the general expense of the framework is to be $89106, simultaneously considering the absolute expenses of sustainable power assets at $427,700, $456,700, and $448,200 for ZOA, MFOA, and SFSN, respectively. In addition, Table 3 records the ideal sizes for PV, and WT units. Figure 5 shows an enhanced power quality in terms of active power loss (kW) with and without RER incorporation through proposed ZOA. When the solar irradiance or the wind speed changed, the PV unit's and WT's power outputs also changed, which can be seen in Figures 6 and 7, respectively. The goal capability union is achieved when ZOA, SFSN, and MFOA were utilized, which is portrayed in Figure 8. By the 30th emphasis, ZOA showed supporting assembly. This demonstrates that ZOA is an amazing asset for tracking down ideal answers for the predefined REEM issue.

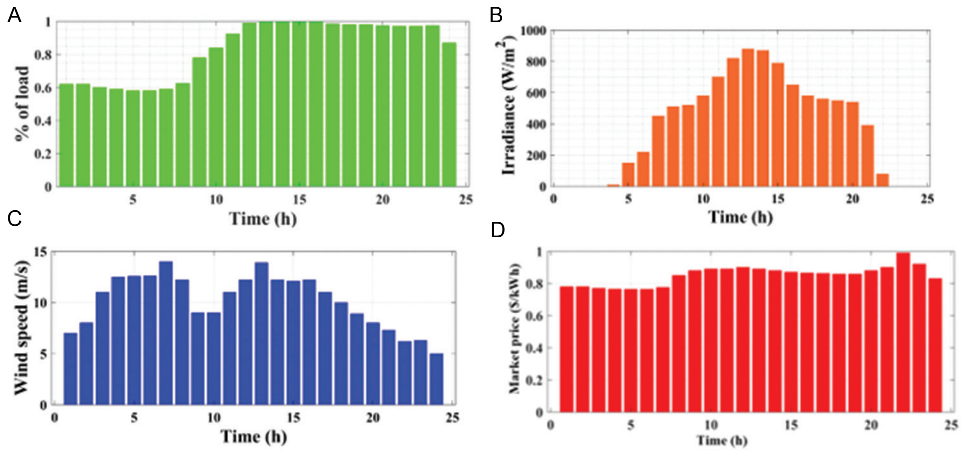

Figure 3. Load profile (A), solar irradiance (B), wind speed (C), market price (D)

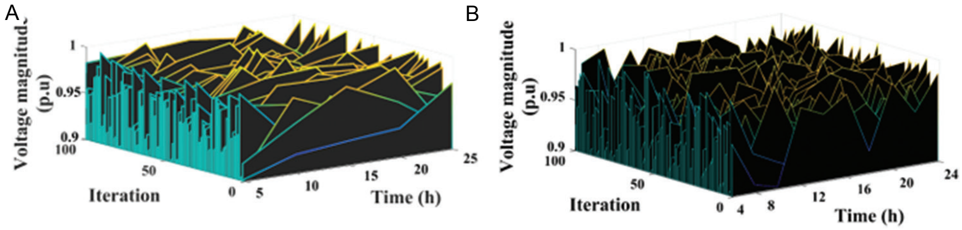

Figure 4. Voltage profiles of a microgrid: (A) Without RER (B) With RER
Abbreviation: RER: Renewable energy resource.

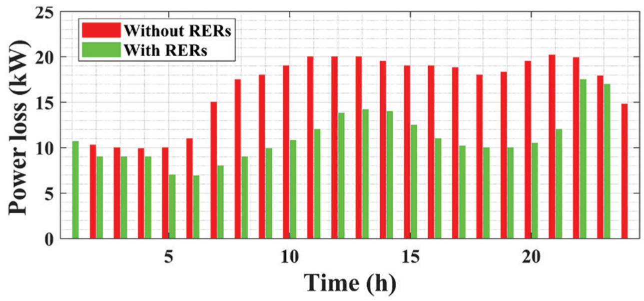

Figure 5. Active power loss (kW)
Abbreviation: RERs: Renewable energy resources.

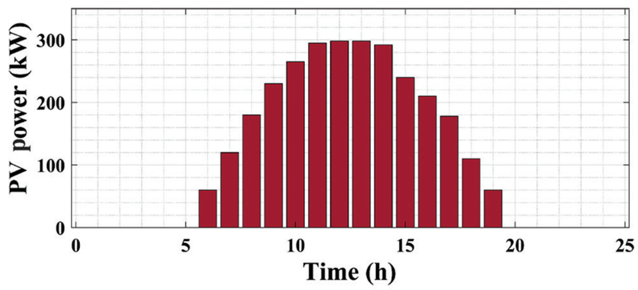

Figure 6. PV power profile
Abbreviation: PV: Photovoltaic.

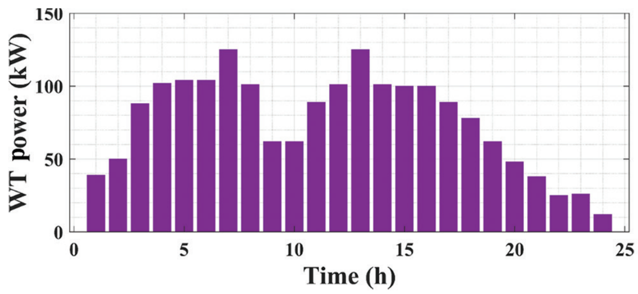

Figure 7. Active power of wind profile
Abbreviation: WT: Wind turbine.

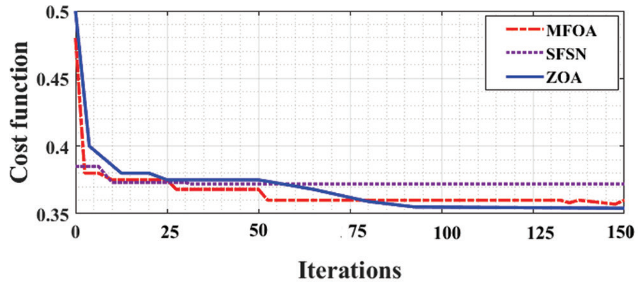

Figure 8. Objective function for MFOA, SFSN, and ZOA
Abbreviations: MFOA: Moth-flame optimization algorithm; SFSN: Stochastic fractal search network; ZOA: Zebra optimization algorithm.

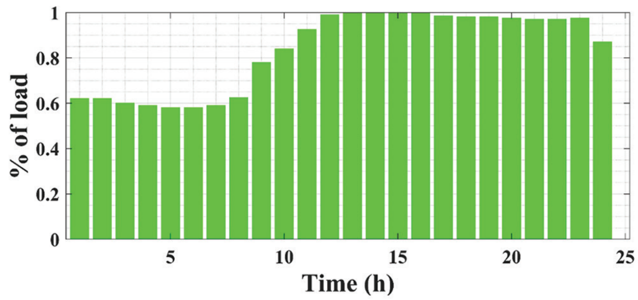

Figure 9. Forecasting of load profile under probabilistic conditions

4.2. Microgrid REEM in a probabilistic scenario

In this work, a method for managing microgrid REEM, which includes wind speed, solar power, and energy demand, is presented. Data on hourly energy demand, sunlight, and wind speed from 3 years are available for study. Wind speed, PV, and the heap profile are displayed in Figures 9 and 10, respectively. Table 5 shows the acquired ideal REEM results involving ZOA strategy in both the situations when RERs are incorporated and without even a trace of them. Without RERs, the general expense, absolute energy (kWh), and the cost of procurement energy from the substation are $3,557,500, $145,688, and $3,548,780, respectively. Taking RERs

Table 4. Results of MGs under various conditions

Specification	Without RERs	ZOA	MFOA	SFSN
Energy losses (kWh)	1.4×10^5	7.434×10^4	7.98140×10^4	7.74459×10^4
The amount of procurement energy from substation (kWh)	3.2088×10^6	1.3802×10^6	1.5356×10^6	1.4434×10^6
PV unit (kW)	-	215	295	230
WT unit (kW)	-	147	135	208
Cost of energy loss ($)	7.0341×10^3	4.7888×10^3	4.6876×10^3	4.6467×10^3
Cost of purchase energy ($)	8.8403×10^5	3.1426×10^5	2.9426×10^5	3.0915×10^5
Cost PV ($)	-	3.71928×10^4	3.23764×10^4	2.90563×10^4
Cost of wind turbine ($)	-	7.15469×10^4	1.25469×10^5	1.05425×10^5
Total cost ($)	0.89106×10^6	0.4277×10^6	0.4567×10^6	0.4482×10^6

Abbreviations: MFOA: Moth-flame optimization algorithm; MGs: Microgrids; PV: Photovoltaic; RERs: Renewable energy resources; SFSN: Stochastic fractal search Network; ZOA: Zebra optimization algorithm.

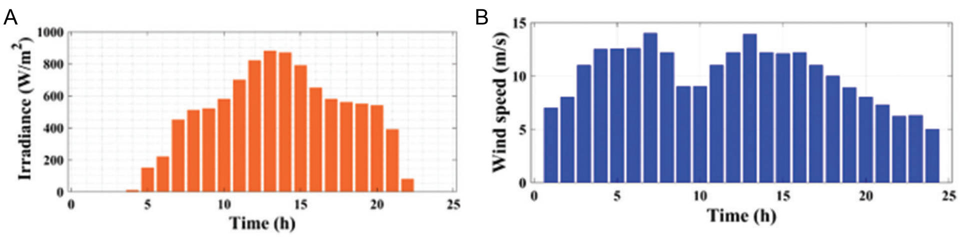

Figure 10. Input profile under probabilistic conditions: (A) PV solar irradiance, and (B) wind speed
Abbreviation: PV: Photovoltaic.

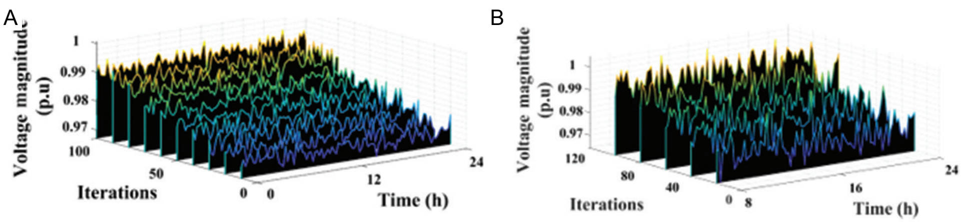

Figure 11. Per unit voltage of a microgrid under probabilistic conditions: (A) without RER, and (B) with RER
Abbreviation: RER: Renewable energy resource.

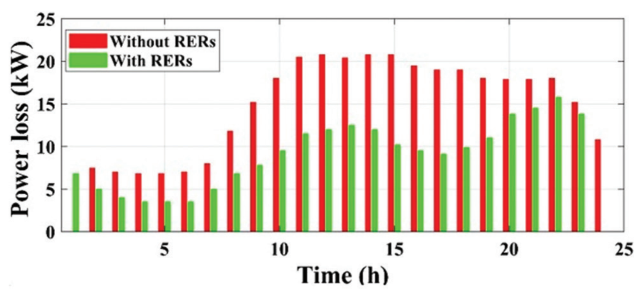

Figure 12. Power losses under probabilistic scenario

into consideration, the ideal sizes (kW) of the PV and WT are 386 and 60, respectively, which are recorded in Table 3. Figure 11 portrays the voltage profiles at various emphasis with and without considering RERs under probabilistic circumstances. The proposed Ideal REEM, regardless of RERs, prompts a better voltage profile. Figure 12 further shows that RERs essentially cut down on power losses (kW). Figure 13A portrays the PV yield power and Figure 13B shows the WT yield power, with both fluctuating with PV illumination and wind speed (Figure 10). A correlation of the two variables uncovers that PV power changes with contrasts in irradiance while WT power changes with variations in turbine speed. Microgrid framework execution and sustainable asset use are both upgraded by the streamlined EM approach that considers vulnerabilities and the RER combination.

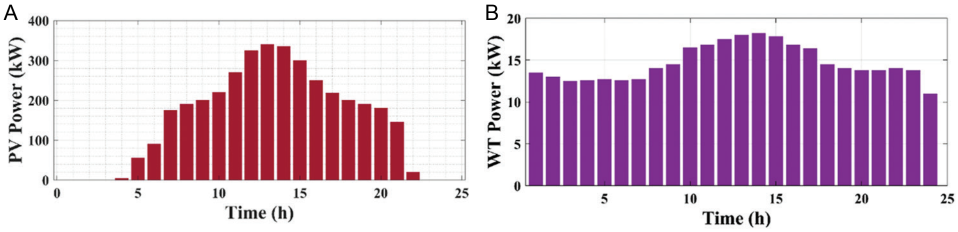

Figure 13. Electric powers for 24-h period: (A) PV, and (B) WT
Abbreviations: PV: Photovoltaic; WT: Wind turbine.

Table 5. REEM simulations of MGs under probabilistic scenario

Parameter	Without RERs	With RERs
The energy losses (kWh)	1.45688×10^5	9.8650×10^4
The procurement energy from the substation (kWh)	3.45787×10^6	2.9501×10^6
Optimization size of the PV unit (kW)	0	386
Optimization size of the WT	0	60
Overall Cost of energy loss ($)	8.74149×10^3	5.18867×10^3
Cost of procurement energy ($)	3.54878×10^6	2.0951×10^6
Cost PV ($)	0	4.83465×10^4
Cost of Wind turbine ($)	0	2.47426×10^4
Total cost ($)	3.5575×10^6	2.17337×10^6

Abbreviations: REEM: Resource efficient energy management; RER: Renewable energy resources; MGs: Microgrids; PV: Photovoltaic; RERs: Renewable energy resources; WT: Wind turbine.

5. Conclusion

In this work, a challenge of REEM in a microgrid was addressed by consolidating PV and WT power frameworks in the most successful way. Under deterministic and probabilistic situations, the ZOA – a compelling streamlining strategy – was utilized to analyze changes sought after for loads, wind speed, PV, and market costs. The proposed ZOA approach further develops the voltage and cost profiles simultaneously following an attempt on developing a 12-transport microgrid framework. An examination was made between the ZOA calculation's result and those of MFOA and SFSN. This examination adds as far as anyone is concerned of the advantages of the ZOA methodology in microgrid REEM applications and features its better exhibition.

This paper exhibits the adequacy of ZOA in tending to difficulties with REEM in microgrids, providing evidence for its capability in streamlining microgrid tasks and its viability in deterministic and probabilistic situations. This features ZOA's strength and flexibility in upgrading microgrid execution.

Ideal reconciliation of RERs into smart EM system (SEMS) has decreased by 52% in general expense under deterministic settings. Simultaneously, the absolute voltage profile has fundamentally dropped by 7.4949%. A critical 63.68% decrease in general expense is accomplished in a probabilistic situation by tending to SEMS through effective fusion of RERs. Simultaneously, the total voltage stability index has improved by 7.51 %.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare that they have no competing interest.

Author contributions

Conceptualization: Dodda Aasha Vardhini
Investigation: Dodda Aasha Vardhini
Methodology: Jayaram Nakka
Writing–original draft: Dodda Aasha Vardhini
Writing–review & editing: Jayaram Nakka

Availability of data

Data are available from the corresponding author on reasonable request.

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Asian Journal of Water, Environment and Pollution. Vol. 22, No. 1 (2025), pp. 134-148.
doi: 10.36922/ajwep.8142

ORIGINAL RESEARCH ARTICLE

Assessment of groundwater quality in Patna district, Bihar, India, using the Water Quality Index method (Canadian Council of Ministers of the Environment method)

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Received: December 23, 2024; Revised: March 2, 2025; Accepted: March 4, 2025; Published online: March 20, 2025

Abstract: In this study, we assessed the groundwater quality in Patna district, Bihar, India, using the Water Quality Index (WQI) method, specifically the Canadian Council of Ministers of the Environment approach. Secondary data from various agencies (2004 – 2020) were analyzed to evaluate physicochemical parameters and spatial-temporal trends. Results indicated that while most samples fell within the permissible limits, samples from some locations showed elevated pH, electrical conductivity, hardness, alkalinity, chloride, and nitrate, suggesting localized contamination from natural and anthropogenic sources. Piper diagram analysis reveals Ca^{2+}-Mg^{2+}-HCO_3^- dominance, pointing to carbonate rock dissolution, with some influence from agricultural and industrial activities. WQI classification categorized 76% of samples as fair to excellent, whereas 24% were marginal to poor. A heatmap analysis highlighted an improvement in water quality after 2012, though water from some stations remained persistently poor. Quantum geographic information system-based spatial mapping using the inverse distance weighting technique effectively visualized pollution hotspots and safe water zones. In conclusion, findings from the study underscore the need for regular monitoring, pollution control, advanced treatment methods, and sustainable groundwater management to ensure safe drinking water.

Keywords: Groundwater; Contamination; Water quality index; Quantum geographic information system; Spatial mapping

1. Introduction

Groundwater is one of the most widely distributed resources on Earth, accounting for approximately 0.6% of the world's total water resources.[1] It is also the largest source of freshwater, making up around 30.1%.[2] As a valuable economic resource, groundwater provides over 85% of public water supplies, primarily sourced from wells.[1] Groundwater is a primary source of drinking water for billions of people worldwide.[3-5] Ecologically, groundwater supports aquatic habitats, maintains river flows, and aids vegetation growth, especially in arid regions.[1,6] Groundwater also regulates soil moisture, preventing desertification.[1,2] In addition, groundwater serves as a buffer against droughts and climate change, ensuring water availability in times of crisis.[1,2]

However, natural and anthropogenic activities, such as climatic and topographical factors, soil erosion, land-use changes, sewage disposal, mining, fertilizers, *etc.*, pose a threatening effect on groundwater quality, impacting its use for domestic, industrial, and agricultural purposes worldwide.[7-11] Unfortunately, these challenges are aggravated by the increasing demand for groundwater due to population growth and urbanization.[12,13] Moreover, waterborne diseases, linked to poor water quality, pose significant health risks.[14]

Groundwater in Patna district, Bihar, is abundant but faces significant quality concerns. In Patna district, groundwater serves as the main source of drinking water. In rural areas, it is typically consumed with little to no treatment. Urban areas lack centralized treatment facilities such as municipal treatment units. Households generally depend on individual water purification methods. Studies have reported contamination exceeding permissible limits for parameters such as total dissolved solids (TDS), total hardness (TH), total alkalinity (TA), Fe^{2+}, As, and F^- renders the groundwater unsuitable for drinking in several locations.[15-18] High concentrations of arsenic and fluoride pose severe health risks, while nitrate contamination from sewage affects multiple districts, including Patna.[19,20] In addition, high levels of iron and alkalinity have been observed in groundwater samples, further deteriorating water quality.[21,22] Reports indicated that certain areas experience seasonal variations in contamination, worsening water security concerns.[23,24] These findings highlight the urgent need for groundwater quality monitoring, pollution control measures, and sustainable water management strategies in the region.

The water quality index (WQI) is a widely used tool to evaluate water quality by consolidating complex data into a single index.[25] It simplifies the analysis by synthesizing and normalizing parameters, providing a comprehensive evaluation of overall water quality status.[26] Various models are employed globally, each featuring variations in the structure, parameters, weighting, and methods of aggregation.[25,26] WQI helps interpret water quality status effectively by highlighting significant parameters and guiding multipurpose water resource use.[26]

The initial WQI model was developed by Horton in the 1960s, concentrating on 10 crucial water quality parameters.[27] Subsequently, Brown expanded Horton's model with the NSF-WQI, integrating insights from 142 water quality experts to refine parameter selection and weighting.[28-30] Later iterations of WQI models, such as the SRDD-WQI developed by the Scottish Research Development Department, evolved from the framework established by the NSF-WQI.[26] Further advancements in this lineage include derivatives such as the Bascaron Index (1979), House Index (1986), and Dalmatian Index.[31] Steinhart *et al.*[32] introduced the Environmental Quality Index for the assessment of Great Lakes ecosystems. Notably, the British Columbia WQI emerged in the mid-90s under the auspices of the British Columbia Ministry for Environment, Lands, and Parks.[33] This model laid the groundwork for the Canadian Council of Ministers of the Environment (CCME) WQI, developed in 2001 by the CCME.[33,34] In addition, various other models such as the Liou Index, Malaysian Index, and Almeida Index have emerged in recent years.[26] Globally, over 35 WQI models have been established by different countries and agencies for the assessment of water quality.[26,29,35-37] Groundwater quality in India is highly variable due to industrial pollution, agricultural runoff, and natural factors.[38] CCME WQI efficiently integrates multiple parameters to reflect the overall condition, making it highly suitable for groundwater assessments in the Patna district.

GIS, or Geographic Information Systems, is a powerful technology used to capture, manage, analyze, and visualize spatial data.[13,39] It integrates various types of information such as maps, satellite imagery, and statistical data, allowing users to understand relationships, patterns, and trends in geographic space.[40] GIS finds applications in fields ranging from urban planning and environmental management to health care and disaster response, providing valuable insights for decision-making and problem-solving.[10,13,39,41-44]

Rapid population growth and urban development in Patna, Bihar, have led to increased water demand due to agricultural and industrial expansion.[45] This has resulted in overexploitation, reduced precipitation, and declining water tables, particularly in densely populated urban areas. To address these challenges, this study focuses on assessing groundwater quality in Patna district using the CCME WQI method. The objectives include data collection from central and state agencies, evaluating WQIs using the CCME method, and visualizing spatial distribution maps of WQIs using Quantum GIS (QGIS) software.

2. Materials and methods

2.1. Study area: Patna district

Patna district in Bihar, India, was selected for groundwater quality assessment based on literature and various sources. A base map (Figure 1) was prepared to

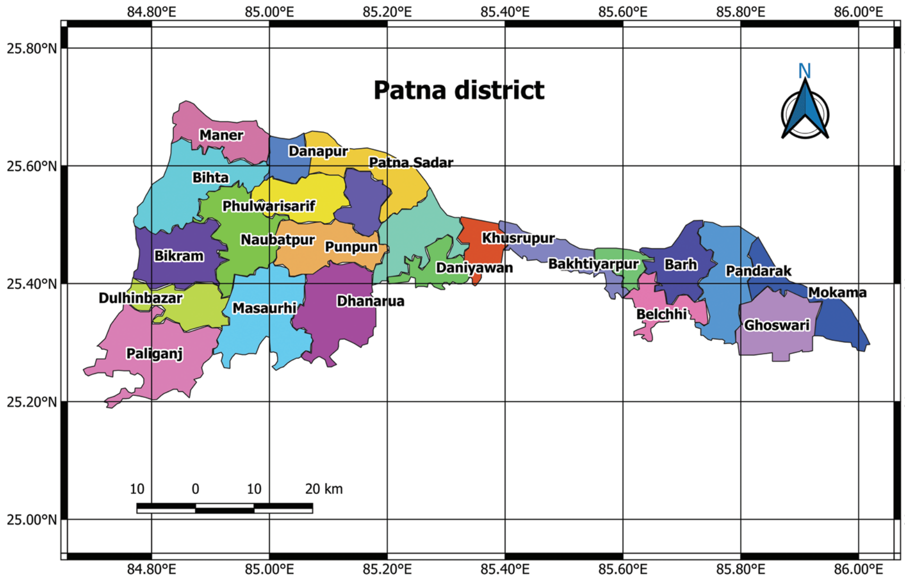

Figure 1. Location map of Patna district

visualize spatial and non-spatial data related to different groundwater quality parameters.

Patna district is situated between 25°13' and 25°45' North latitude and 84°43' and 86°44' East longitude, with an elevation of 67 m above mean sea level, nestled within the South Bihar alluvial plains.[46] It is bordered by the Ganges to the north and neighboring Jahanabad, Nalanda, Lakhisarai, and Bhojpur districts.[46] The district encompasses an area of 3172 sq. km and is divided administratively into six subdivisions, 23 blocks, 344 panchayats, and 1433 villages, as illustrated in Figure 1.[46]

The district experiences an average annual rainfall of approximately 1076 mm, contributing to its overall favorable groundwater potential.[46] Depth to the piezometric surface ranges from 6.25 m to 16.30 m, indicating accessible groundwater.[46,47] Deep tube wells accessing these aquifers can yield from 260 m^3/h to 1500 m^3/h with a drawdown of 6 m.[46,47] The aquifer's transmissivity varies from 3786 to 19540 m^2/day, highlighting its varying capacity for water transmission.[46,47]

2.2. CCME WQI method

The CCME-WQI employs the following parameters to assess stream water quality: Temperature, conductivity, color, turbidity, dissolved oxygen, pH, alkalinity, calcium (Ca), sodium (Na), magnesium (Mg), potassium (K), sulfate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), dissolved organic carbon, phosphorus (P), nitrates, nitrites, nitrogen (N), silica dioxide (SiO_2), aluminum (Al), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), strontium (Sr), vanadium (V), and zinc (Zn).[28,33,48] These parameters are assessed using three main factors, denoted as F_1, F_2, and F_3, which are determined directly through the application of specific formulae.[28,33]

F_1 represents the proportion of variables that fail to meet the objectives at least once during the specified period (referred to as failed variables), typically computed using the following formula:

$$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables} \right) \times 100 . \quad \text{(I)}$$

F_2 represents the percentage of individual tests that do not meet the goals at any point (referred to as failed tests).

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests} \right) \times 100 . \quad \text{(II)}$$

F_3 is the factor that signifies the extent to which test values deviate from their guideline values. This calculation involves three steps:

- Step 1: When the test value must not exceed the objective:

$$\text{Excursion} = \left(\frac{Failed\ test\ value}{Objective} \right) - 1 ; \quad \text{(III)}$$

- Step 2: When the test value must not fall below the objective:

$$\text{Excursion} = \left(\frac{Objective}{Failed\ test\ value}\right) - 1; \quad \text{(IV)}$$

- Step 3: The total sum of excursions (normalized sum of excursions, nse) beyond compliance is determined using the following formulae:

$$\text{nse} = \left(\frac{\sum_{i=1}^{n} excursion}{Number\ of\ test}\right); \quad \text{(V)}$$

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right). \quad \text{(VI)}$$

After establishing these factors, the CCME-WQI can be computed using the following formula:

$$\text{CWQI} = 100 - \left(\frac{\sqrt{(F_1)^2 + (F_2)^2 + (F_3)^2}}{1.732}\right). \quad \text{(VII)}$$

The value derived from computing the index using the aforementioned formulae can classify the analyzed water into one of the specific quality categories outlined in Table 1.

2.3. Groundwater quality data collection

All the information related to the present study such as population data, groundwater quantity status, groundwater quality status, drinking water quality standards, and guidelines had been collected from various central and state agencies. Some of the major agencies providing secondary data are enlisted here:

- Ground Water Yearbook-India, Central Ground Water Board (published from 2009 to 2020)
- ENVIS Centre on Control of Pollution Water, Air and Noise, Central Ground Water Board
- ENVIS Centre, Bihar State Pollution Control Board, Patna (Bihar)
- India Water Resources Information System, Department of Water Resource, GoI.

Table 1. Water quality rating as per CCME WQI method

Value of WQI	Quality of water
95 – 100	Excellent
80 – 94	Good
60 – 79	Fair
45 – 59	Marginal
0 – 44	Poor

Abbreviations: CCME: Canadian Council of Ministers of the Environment; WQI: Water Quality Index.

2.4. Software

2.4.1. QGIS

To analyze different spatial and non-spatial data, an open-source software named QGIS version 3.18.1 (Zürich) was used.

2.4.2. Microsoft office tools

For arranging and analyzing the data, some of the tools from Microsoft Office such as Word, Excel, and PowerPoint were used in this study.

3. Results and discussion

3.1. Groundwater quality data collection

The data for several groundwater quality parameters were collected from various central and state agencies from 2004 to 2020. These data were further processed in Microsoft Excel to use in the QGIS application as well as in the WQI calculation.

3.2. Physicochemical characteristics of groundwater in Patna district

The secondary groundwater quality data collected from various sources includes the following water quality parameters: pH, electrical conductivity (EC), TH, TA, TDSs, carbonates and bicarbonates, chloride, sulfate, nitrate, calcium, magnesium, sodium, potassium, and fluoride concentrations. The statistical results of the physicochemical water quality parameters are tabulated in Table 2.

Based on Table 2, pH ranges from 6.90 to 9.20, with some samples exceeding the permissible limit (6.5 – 8.5), indicating alkaline water. High EC (242 – 2050 µS/cm) and TDS (114 – 1163.50 mg/L) in some locations suggest elevated dissolved ion concentrations. TH (90 – 816 mg/L) and alkalinity (112 – 694.90 mg/L) often exceed limits, leading to potential scaling and taste issues. Higher concentrations of chloride (up to 337.40 mg/L) and nitrate (up to 111 mg/L) in some samples indicate contamination from sewage and agriculture. Calcium and magnesium exceed the 75 and 30 mg/L limits, respectively, in several cases, contributing to water hardness. However, fluoride concentrations are found to be mostly within safe limits (0.08 – 1.05 mg/L), reducing fluorosis risk. While many parameters remain within limits, high pH, hardness, alkalinity, and nitrate levels in certain areas indicate localized contamination,[49] regular monitoring and treatment are recommended to ensure safe drinking water.

Table 2. Physicochemical characteristics of groundwater samples (2004 – 2020)

Characteristics of groundwater	Min.	Max.	Average	SD	Permissible limit as per IS 10500:2012
pH value	6.90	9.20	7.87	0.51	6.5 – 8.5
Electrical conductivity, µS/cm	242.00	2050.00	853.24	406.32	--
Total hardness, mg/L as $CaCO_3$	90.00	816.00	256.83	149.22	200
Total alkalinity, mg/L as $CaCO_3$	112.00	694.90	262.51	143.10	200
TDS, mg/L	114.00	1163.50	419.37	286.00	500
Carbonates, mg/L as $CaCO_3$	0.00	72.00	7.67	16.43	--
Bicarbonates, mg/L as $CaCO_3$	50.14	738.00	296.60	136.65	--
Chloride, mg/L	3.50	337.40	74.68	66.16	250
Sulphate, mg/L	0.00	144.10	43.45	42.56	200
Nitrate, mg/L	0.00	111.00	9.58	19.26	45
Calcium, mg/L	2.04	139.40	43.47	27.82	75
Magnesium, mg/L	3.60	118.66	34.91	24.12	30
Sodium, mg/L	9.54	215.00	74.24	48.47	--
Potassium, mg/L	0.00	80.80	8.40	15.58	--
Fluoride, mg/L	0.08	1.05	0.48	0.23	1

Abbreviations: SD: Standard deviation, TDS: Total dissolved solids.

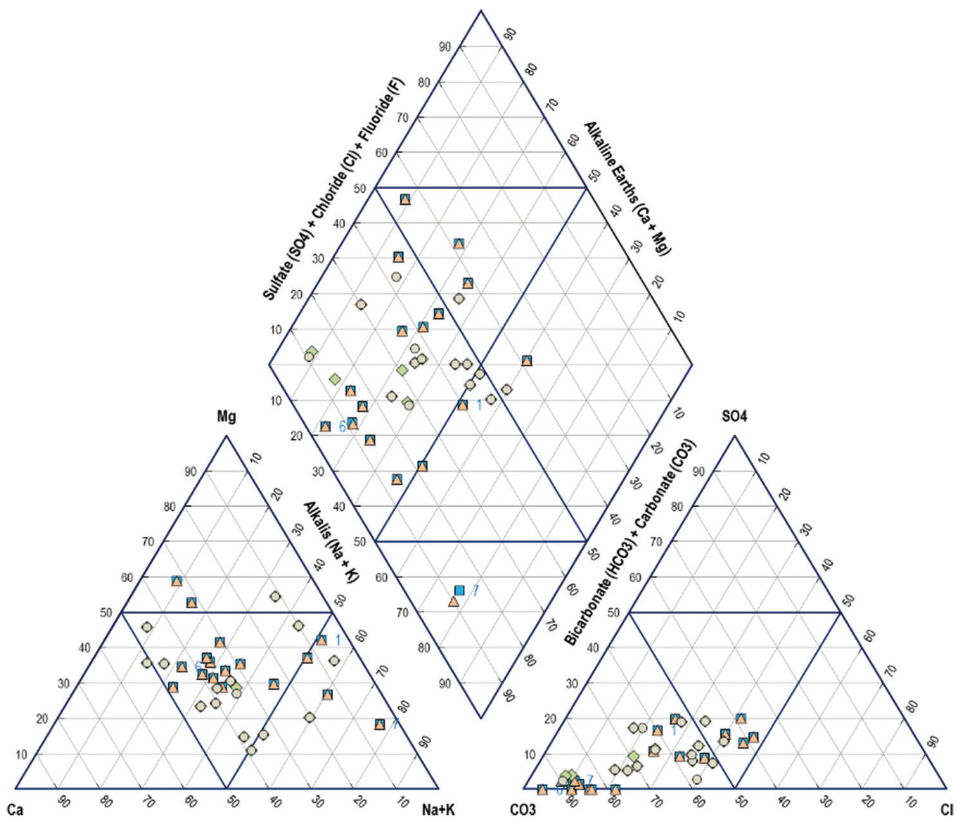

Figure 2. Piper diagram

The Piper diagram presented provides a graphical representation of groundwater chemistry in the Patna district (Figure 2). Most of the groundwater samples show a dominance of Ca^{2+} and Mg^{2+}, indicating the influence of carbonate minerals such as limestone or dolomite. Some samples are enriched in Na^{+} and K^{+}, an indication of ion exchange processes or interaction with silicate minerals. The predominant anions are HCO_3^{-} and CO_3^{-}, signifying bicarbonate-type water commonly associated with carbonate rock dissolution. Some samples also exhibit Cl^{-} and SO_4^{2-} dominance, indicating potential anthropogenic influences (e.g., agricultural runoff, industrial discharge) or evaporite dissolution. Most of the samples fall in the Ca^{2+}-Mg^{2+}-HCO_3^{-} region, indicating fresh groundwater influenced by carbonate weathering. A few samples trend toward the Na^{+}-Cl^{-} and SO_4^{2-} zones, suggesting mixing with saline water, possible anthropogenic contamination, or groundwater evolution due to ion exchange. The dominance of Ca^{2+}-Mg^{2+}-HCO_3^{-} water type is typical of groundwater in areas influenced by carbonate rocks. The presence of Cl^{-} and SO_4^{2-}-rich samples indicates potential salinity issues or pollution sources.

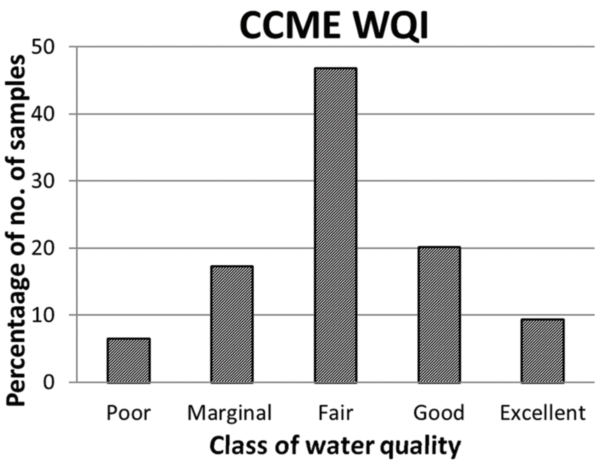

Figure 3. Percentage distribution of water samples as per CCME WQI classification

Abbreviations: CCME: Canadian Council of Ministers of the Environment; WQI: Water Quality Index.

3.3. Measuring WQI of Patna district using CCME method

The available and processed groundwater quality parameters (2004 – 2020) are analyzed and converted to suitable WQIs as per the CCME method. The groundwater of Patna district was further classified into different categories based on the different values of WQ indices using the CCME method, as shown in Table 3.

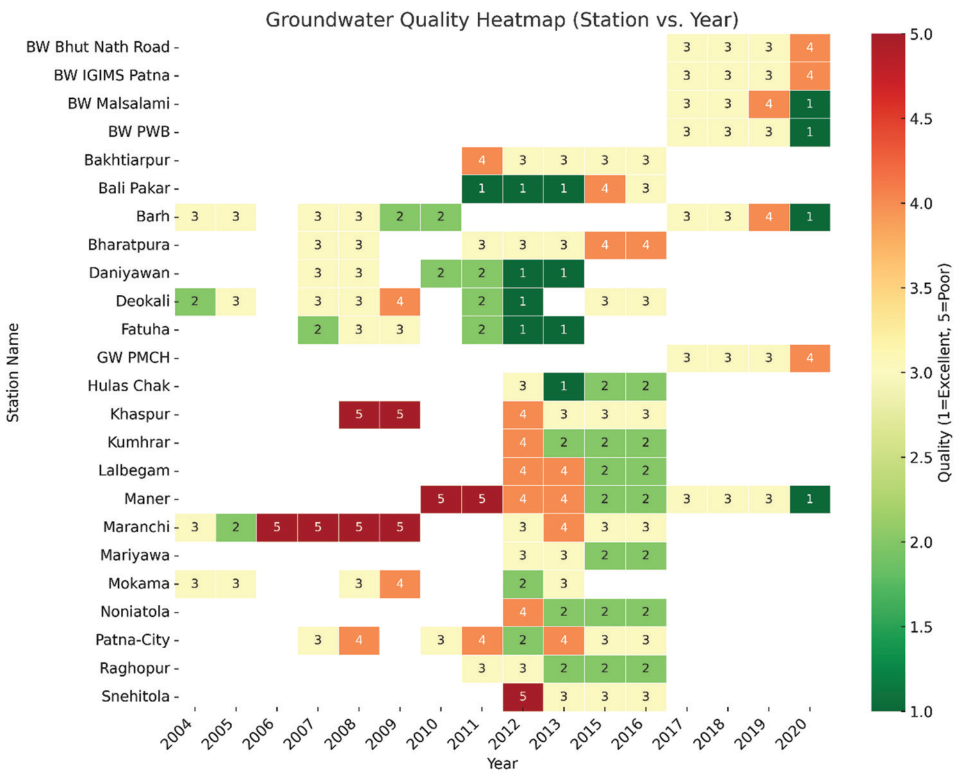

Figure 4. Groundwater quality heatmap

Table 3. WQI of different stations of Patna from 2004 to 2020 measured using the CCME method

Year	No. of stations	Station	Latitude	Longitude	WQI	Result
2004	4	Barh 1	85.706	25.464	79.36	Fair
		Deokali	85.018	25.452	80.77	Good
		Maranchi	85.987	25.354	62.32	Fair
		Mokama	85.987	25.504	63.50	Fair
2005	4	Barh 1	85.706	25.464	79.36	Fair
		Deokali	85.018	25.452	62.32	Fair
		Maranchi	85.987	25.354	80.77	Good
		Mokama	85.987	25.504	63.51	Fair
2006	1	Maranchi	85.987	25.354	26.77	Poor
2007	7	Barh 1	85.706	25.464	63.14	Fair
		Bharatpur	84.862	25.342	63.48	Fair
		Daniyanwan	85.311	25.436	76.96	Fair
		Deokali	85.018	25.452	76.77	Fair
		Fatuha	85.294	25.505	81.87	Good
		Maranchi	85.987	25.354	31.44	Poor
		Patna City	85.591	25.243	71.66	Fair
2008	9	Barh 1	85.706	25.464	63.14	Fair
		Bharatpur	84.862	25.342	63.49	Fair
		Daniyanwan	85.311	25.436	76.96	Fair
		Deokali	85.018	25.452	62.51	Fair
		Fatuha	85.294	25.505	79.36	Fair
		Khaspur	85.005	25.638	31.03	Poor
		Maranchi	85.987	25.354	31.31	Poor
		Mokama	85.987	25.504	72.85	Fair
		Patna City	85.591	25.243	53.25	Marginal
2009	6	Barh 1	85.706	25.464	80.58	Good
		Deokali	85.018	25.452	54.32	Marginal
		Fatuha	85.294	25.505	75.99	Fair
		Khaspur	85.005	25.638	31.03	Poor
		Maranchi	85.987	25.354	31.31	Poor
		Mokama	85.987	25.504	53.25	Marginal
2010	4	Barh 1	85.706	25.464	80.58	Good
		Daniyanwan	85.311	25.436	80.35	Good
		Maner	84.887	25.636	40.97	Poor
		Patna City	85.591	25.243	79.36	Fair
2011	9	Bakhtiyarpur	85.529	25.464	49.97	Marginal
		Bali Pakar	84.826	25.332	100.00	Excellent
		Bharatpur	84.862	25.342	63.52	Fair
		Daniyanwan	85.311	25.436	83.57	Good
		Deokali	85.018	25.452	83.43	Good
		Fatuha	85.294	25.505	82.56	Good

(Cont'd...)

Table 3. ***(Continued)***

Year	No. of stations	Station	Latitude	Longitude	WQI	Result
		Maner	84.887	25.636	41.50	Poor
		Patna City	85.591	25.243	48.63	Marginal
		Raghopur	84.862	25.548	65.21	Fair
2012	18	Bakhtiyarpur	85.529	25.464	64.25	Fair
		Bali Pakar	84.826	25.332	100.00	Excellent
		Bharatpur	84.862	25.342	73.30	Fair
		Daniyanwan	85.311	25.436	100.00	Excellent
		Deokali	85.018	25.452	100.00	Excellent
		Fatuha	85.294	25.505	100.00	Excellent
		Hulas Chak	85.025	25.538	63.34	Fair
		Khaspur	85.005	25.638	55.15	Marginal
		Kumhrar	85.184	25.602	48.65	Marginal
		Lalbegam	84.975	25.653	48.52	Marginal
		Maner	84.887	25.636	47.67	Marginal
		Maranchi	85.987	25.354	73.19	Fair
		Mariyawa	84.864	25.493	60.78	Fair
		Mokama	85.987	25.504	85.34	Good
		Noniatola	84.870	25.422	59.12	Marginal
		Patna City	85.591	25.243	86.00	Good
		Raghopur	84.862	25.548	60.25	Fair
		Snehitola	84.960	25.507	41.73	Poor
2013	17	Bakhtiyarpur	85.529	25.464	64.25	Fair
		Bali Pakar	84.826	25.332	100.00	Excellent
		Bharatpur	84.862	25.342	73.30	Fair
		Daniyanwan	85.311	25.436	100.00	Excellent
		Fatuha	85.294	25.505	100.00	Excellent
		Hulas Chak	85.025	25.538	100.00	Excellent
		Khaspur	85.005	25.638	60.34	Fair
		Kumhrar	85.184	25.602	85.15	Good
		Lalbegam	84.975	25.653	48.65	Marginal
		Maner	84.887	25.636	48.52	Marginal
		Maranchi	85.987	25.354	57.67	Marginal
		Mariyawa	84.864	25.493	73.91	Fair
		Mokama	85.987	25.504	60.72	Fair
		Noniatola	84.870	25.422	85.34	Good
		Patna City	85.591	25.243	59.13	Marginal
		Raghopur	84.862	25.548	86.00	Good
		Snehitola	84.960	25.507	60.25	Fair
2015	15	Bakhtiyarpur	85.529	25.464	75.94	Fair
		Bali Pakar	84.826	25.332	53.69	Marginal
		Bharatpur	84.862	25.342	49.43	Marginal

(Cont'd...)

Table 3. ***(Continued)***

Year	No. of stations	Station	Latitude	Longitude	WQI	Result
		Deokali	85.018	25.452	72.55	Fair
		Hulas Chak	85.025	25.538	87.32	Good
		Khaspur	85.005	25.638	71.95	Fair
		Kumhrar	85.184	25.602	86.05	Good
		Lalbegam	84.975	25.653	89.21	Good
		Maner	84.887	25.636	85.42	Good
		Maranchi	85.987	25.354	71.31	Fair
		Mariyawa	84.864	25.493	88.93	Good
		Noniatola	84.870	25.422	82.99	Good
		Patna City	85.591	25.243	75.33	Fair
		Raghopur	84.862	25.548	89.12	Good
		Snehitola	84.960	25.507	74.46	Fair
2016	15	Bakhtiyarpur	85.529	25.464	74.46	Fair
		Bali Pakar	84.826	25.332	62.32	Fair
		Bharatpur	84.862	25.342	49.43	Marginal
		Deokali	85.018	25.452	72.55	Fair
		Hulas Chak	85.025	25.538	87.32	Good
		Khaspur	85.005	25.638	71.95	Fair
		Kumhrar	85.184	25.602	86.05	Good
		Lalbegam	84.975	25.653	89.51	Good
		Maner	84.887	25.636	85.42	Good
		Maranchi	85.987	25.354	79.31	Fair
		Mariyawa	84.864	25.493	88.93	Good
		Noniatola	84.870	25.422	82.99	Good
		Patna City	85.591	25.243	75.33	Fair
		Raghopur	84.862	25.548	89.12	Good
		Snehitola	84.960	25.507	74.46	Fair
2017	7	Bhut Nath Road, Water Tank Sec-3, Kankarbagh	85.175	25.592	71.38	Fair
		Katra Bazar, Water Tank, Malsalami, Patna	85.253	25.580	71.03	Fair
		IGIMS Campus, Patna	85.090	25.612	78.24	Fair
		Water Board Head Office, Near High Court, Patna	85.138	25.610	77.77	Fair
		Barh	85.705	25.473	66.15	Fair
		Maner	84.872	25.647	77.08	Fair
		Overhead Tank, PMCH Campus, Patna	85.161	25.620	78.48	Fair
2018	7	Bhut Nath Road, Water Tank Sec-3, Kankarbagh	85.175	25.592	71.17	Fair
		Katra Bazar, Water Tank, Malsalami, Patna	85.253	25.580	77.60	Fair
		IGIMS Campus, Patna	85.090	25.612	70.58	Fair
		Water Board Head Office, Near High Court, Patna	85.138	25.610	70.14	Fair
		Barh	85.705	25.473	68.51	Fair
		Maner	84.872	25.647	61.31	Fair
		Overhead Tank, PMCH Campus, Patna	85.161	25.620	77.77	Fair

(Cont'd...)

Table 3. ***(Continued)***

Year	No. of stations	Station	Latitude	Longitude	WQI	Result
2019	7	Bhut Nath Road, Water Tank Sec-3, Kankarbagh	85.175	25.592	70.23	Fair
		Katra Bazar, Water Tank, Malsalami, Patna	85.253	25.580	56.47	Marginal
		IGIMS Campus, Patna	85.090	25.612	76.45	Fair
		Water Board Head Office, Near High Court, Patna	85.138	25.610	75.62	Fair
		Barh	85.705	25.473	48.01	Marginal
		Maner	84.872	25.647	76.46	Fair
		Overhead Tank, PMCH Campus, Patna	85.161	25.620	76.55	Fair
2020	7	Bhut Nath Road, Water Tank Sec-3, Kankarbagh	85.175	25.592	56.02	Marginal
		Katra Bazar, Water Tank, Malsalami, Patna	85.253	25.580	100.00	Excellent
		IGIMS Campus, Patna	85.090	25.612	57.57	Marginal
		Water Board Head Office, Near High Court, Patna	85.138	25.610	100.00	Excellent
		Barh	85.705	25.473	100.00	Excellent
		Maner	84.872	25.647	100.00	Excellent
		Overhead Tank, PMCH Campus, Patna	85.161	25.620	57.57	Marginal

Abbreviations: CCME: Canadian Council of Ministers of the Environment; WQI: Water Quality Index.

From the data, as shown in Table 3, it has been observed that approximately 76% of water samples from 106 locations come under the fair to excellent water quality category during 2004 – 2020, and approximately 24% of water samples from 33 locations fall into marginal to bad water quality category.

Figure 3 also shows the percentage distribution of sample locations into different water quality classes using the CCME method.

To evaluate the spatial trends in groundwater quality over time, a heatmap (Station vs. Year) was generated, as shown in Figure 4. The number of stations classified as "Excellent (E)" or "Good (G)" has increased since 2011, whereas earlier years (2004 – 2010) were predominantly categorized as "Fair (F)" or "Marginal (M)." The highest occurrence of "Poor (P)" and "Marginal (M)" classifications was observed between 2008 and 2012, followed by a decline, suggesting improved management, reduced pollution, or natural attenuation of contaminants. Recent trends (2017 – 2020) indicated that most stations are now classified as "Fair (F)" or better. In 2020, four stations achieved "Excellent (E)" status, and none were classified as "Poor (P)." While some stations showed an overall improvement in groundwater quality, others displayed fluctuations likely influenced by seasonal variations or human activities. A few stations continued to exhibit poor water quality, highlighting persistent contamination concerns.

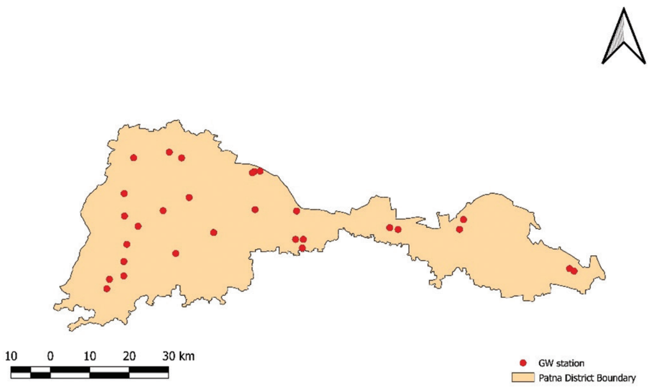

Figure 5. Locations of groundwater quality data sourced from various agencies for this study

3.4. WQI mapping using QGIS

Groundwater quality maps play a crucial role in evaluating the suitability of water for various uses, with a primary emphasis on drinking water. A 2D visualization of the physicochemical characteristics of groundwater in the Patna district was developed using the QGIS software. Groundwater quality data were gathered from multiple central and state agencies and subsequently processed in Microsoft Excel for use in the QGIS application. In addition, a vector layer represents the sampling locations for various groundwater quality parameters, as illustrated in Figure 5.

Inverse Distance Weighting (IDW) in QGIS is a widely used interpolation technique for groundwater assessment mapping, particularly for generating WQI maps. IDW estimates unknown values based on

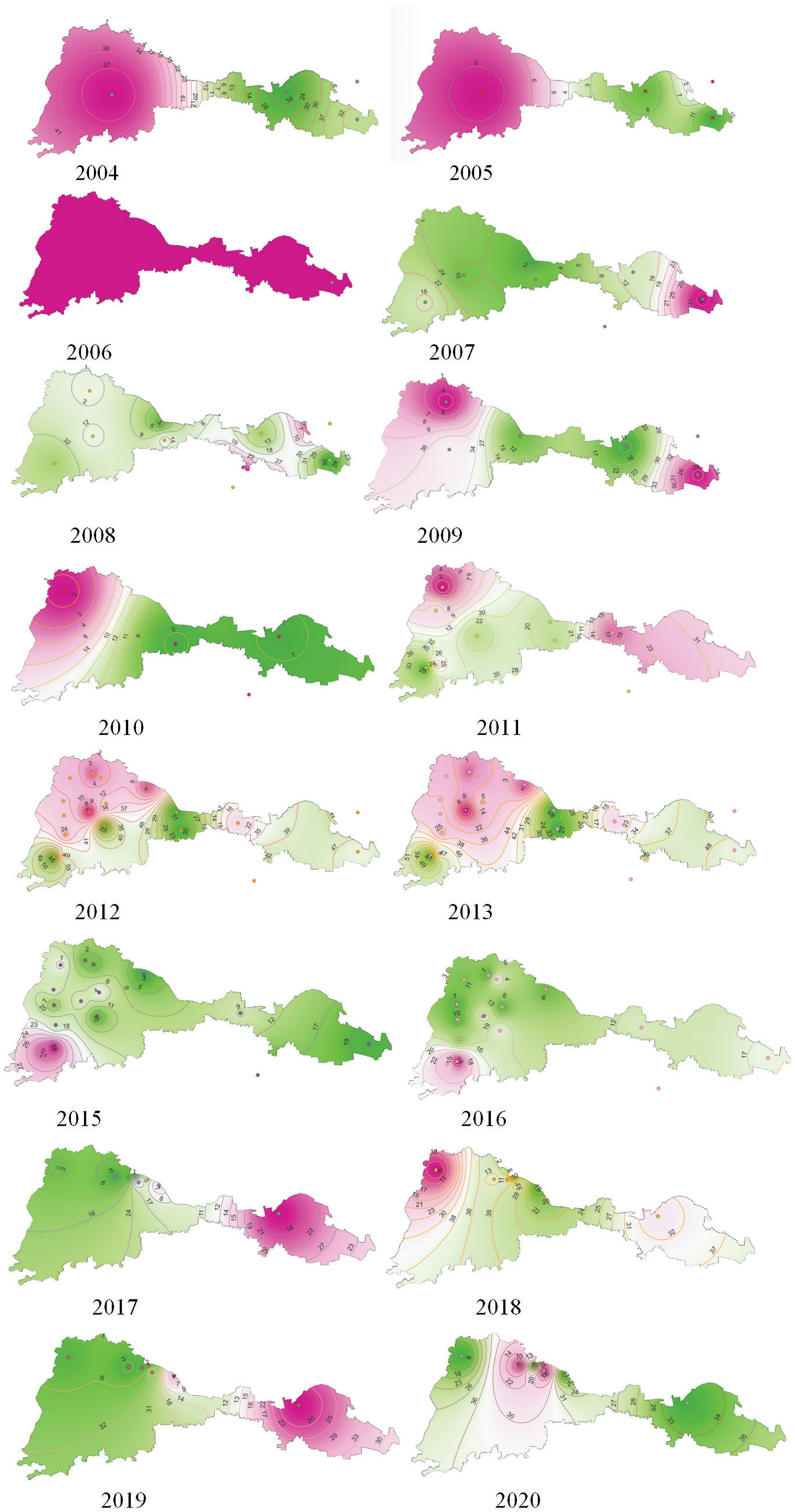

Figure 6. Spatial distribution of WQI using the CCME method (2004 – 2020)

Abbreviations: CCME: Canadian Council of Ministers of the Environment; WQI: Water Quality Index.

nearby sampled data, assuming that closer points have a greater influence on the predicted values. It helps visualize spatial variations in groundwater quality, identifies contamination zones, and supports decision-making in water resource management. The method is simple and easy to use, making it effective for WQI mapping. However, IDW is highly dependent on data distribution, and its accuracy can be affected by the choice of power value and the number of neighbors considered. Despite its limitations, IDW is valuable for assessing groundwater quality, identifying pollution hotspots, and monitoring spatial variations over time, aiding in effective groundwater resource management.

The calculated WQIs were further used in QGIS to obtain the spatial distribution of groundwater quality in terms of WQI. The water quality mapping using the IDW interpolation technique helps to visualize the zones of critically polluted groundwater resources in a better way. Furthermore, these maps can be helpful to find and protect groundwater zones having good quality water. The spatial distribution of groundwater qualities in terms of WQI calculated by the CCME method is shown in Figure 6.

Data interpretation enabled by the mapping approach is more convenient than that through the tabular presentation method, allowing the public to analyze water quality in their respective regions with ease. The QGIS software makes it quite easy to analyze and edit spatial information and relate WQI data through different timelines.

Groundwater modeling serves as a valuable tool in obtaining analytical solutions for assessing the quality of groundwater.[50-53] Integrating analytical models for both point and non-point sources of pollutants alongside WQI models facilitates the visualization and identification of potential solute transport behavior.[54-58] These methodologies hold promise in safeguarding the integrity of aquifers.

Groundwater in Patna district faces quality issues due to high EC, TDS, hardness, alkalinity, chloride, and nitrate, which can impact both human health and water usability. These contaminants mainly originate from natural geological formations, agricultural runoff, industrial discharges, and sewage infiltration. To ensure long-term groundwater sustainability and maintain high water quality, the following measures have been suggested:

(i) *Source control and pollution prevention*
- Regulation of industrial and agricultural activities: Strict enforcement of wastewater treatment laws and sustainable farming practices (e.g., controlled fertilizer use, organic alternatives, drip irrigation) to reduce groundwater contamination
- Sewage and wastewater management: Improving sewage treatment infrastructure to prevent leaching nitrates, chlorides, and other contaminants into groundwater.

(ii) *Water treatment technologies*
- Reverse osmosis (RO) and ion exchange: Effective for removing excess TDS, hardness, chloride, and nitrates from drinking water, especially in high-contamination areas
- Lime-soda treatment: Helps in reducing water hardness and alkalinity by precipitating calcium and magnesium
- Biological denitrification: Using microbes to convert nitrates into harmless nitrogen gas, reducing groundwater pollution.

(iii) *Artificial recharge and dilution techniques*
- Rainwater harvesting and managed aquifer recharge: Large-scale implementation of recharge wells and percolation tanks to dilute high TDS, hardness, and chloride concentrations in groundwater.

(iv) *Public awareness and policy interventions*
- Regular water quality monitoring: Establishing systematic groundwater quality assessments and early warning systems
- Public awareness campaigns: Educating communities about water contamination risks and promoting household-level filtration methods (e.g., RO purifiers, activated carbon filters)
- Government regulations and sustainable practices: Strengthening groundwater protection policies, encouraging sustainable industrial and agricultural practices, and promoting better urban water management strategies.

4. Conclusion

The present study focuses on investigating groundwater quality issues in Patna district, Bihar, India, using the WQI method, particularly the CCME method. Secondary data were collected from various state and central agencies to assess groundwater quality trends from 2004 to 2020. Initially, in 2004, the number of sampling locations was limited, restricting comprehensive water quality analysis. However, in later years, the increased number of sampling locations allowed for a more detailed assessment. Variations in sampling stations over different years may have introduced some discrepancies in the results.

The groundwater quality assessment of the Patna district from 2004 to 2020 revealed significant spatial and temporal variations in physicochemical parameters. While the majority of the groundwater samples fell within the permissible limits for these parameters, water samples from certain locations exhibited elevated pH, EC, TH, alkalinity, chloride, nitrate, and other key contaminants, indicating localized contamination due to natural and anthropogenic influences. The Piper diagram analysis confirms that the dominant water type is Ca^{2+}-Mg^{2+}-HCO_3^-, suggesting carbonate rock dissolution as a major controlling factor, with some samples showing anthropogenic influences such as agricultural runoff and industrial discharge.

With the WQI analysis using the CCME method, approximately 76% of the water samples were classified as fair to excellent, whereas 24% fell into the marginal to poor categories, emphasizing the need for targeted monitoring and remediation efforts in affected areas. On the other hand, the heatmap shows improving groundwater quality since 2011, with fewer poor stations after 2012. By 2020, water from most stations was "fair" or better, though water from some, such as Maranchi and Khaspur, remained persistently poor.

Spatial mapping of WQI in QGIS using the IDW interpolation technique provides an effective visualization of groundwater quality, making it easier to identify critical pollution zones and areas with good water quality. While QGIS proves to be an effective tool for groundwater quality assessment, further analysis can be enhanced with the availability of additional essential parameters. The integration of groundwater quality mapping with analytical models aids in better understanding solute transport behavior, thereby supporting informed decision-making for sustainable groundwater resource management. Regular monitoring and proper treatment measures are crucial for ensuring safe and sustainable groundwater use in the region.

Groundwater quality in the Patna district is impacted by high EC, TDS, hardness, alkalinity, chloride, and nitrate, mainly due to agricultural runoff, industrial discharge, and sewage infiltration. Effective management of groundwater in Patna district requires pollution control, advanced treatment methods, artificial recharge, and public awareness.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Bandana Mahto, Premlata Singh
Formal analysis: Bandana Mahto, Baboo Rai
Investigation: Bandana Mahto
Methodology: Bandana Mahto, Premlata Singh
Writing – original draft: Bandana Mahto
Writing – review & editing: All authors

Availability of data

The data are available upon request to the corresponding author.

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Asian Journal of Water, Environment and Pollution Vol. 22, No. 1 (2025), pp. 149-165.
doi: 10.36922/AJWEP025040017

ORIGINAL RESEARCH ARTICLE

Securing smart health in smart cities: Blockchain technology to secure electronic health data sharing

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(This article belongs to the *Special Issue: Renewable Energy Systems and Strategies in Smart Grids and Smart Cities Development*)

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Received: January 20, 2025; Revised: February 14, 2025; Accepted: February 25, 2025; Published online: March 24, 2025

Abstract: In the era of smart cities, safeguarding electronic health records (EHRs) is crucial to ensure the privacy and security of citizens' sensitive medical information. Existing medical data transfer methods are vulnerable to privacy breaches, making it challenging to protect patient data. This research proposes a novel blockchain-based approach to secure EHR sharing in smart cities. Our method leverages improved association rule mining to identify sensitive information, which is then encrypted using the Siberian Tiger Integrated Tuna Swarm algorithm to generate an optimal encryption key. The encrypted data are stored on a blockchain, ensuring its integrity and confidentiality. Our proposed model demonstrates maximum robustness against various attacks, including chosen ciphertext attack, chosen-plaintext attack, known ciphertext attack, and known-plaintext attack. This research contributes to the development of secure and privacy-preserving smart health infrastructure in smart cities, enabling the safe sharing of EHRs and promoting better health-care outcomes.

Keywords: Medical data; Improved association rule mining; Blockchain; Optimal key; Siberian tiger integrated tuna swarm algorithm optimization

1. Introduction

Health-care-related data are produced, saved, and used extensively in large quantities. Electronic health records (EHRs) are one of the most significant components of health-care systems, offering numerous benefits to health-care stakeholders.[1-3] For instance, it saves patients from costly testing, radiography, and recurrent imaging while enabling them to access their medical information. Furthermore, clinicians across different health-care institutions can use EHR to access patient information, even if the patient receives care in separate locations. In addition, EHRs allow doctors to review a patient's past medication history, aiding in prescription recommendations.[4-6] The utilization of patient medical information for research of novel treatment approaches is another benefit of employing EHRs.

Ensuring patient privacy is a fundamental concern while utilizing EHRs in the health-care industry[7-9] due to the widespread access to medical information. An additional challenge for EHR is that patients do not own their data; instead, the medicinal centers hold ownership of patient data. A key issue regarding patient privacy is that medical professionals and investigators can access their EHR without the patient's consent.[10,11] From a security standpoint, several challenges arise with the use of EHRs.[12,13] These issues can potentially be addressed through the use of blockchain technology

(BT). BT is an effective distributed ledger system for effectively recording transactions between two parties. Every transaction is stored in a "block," and these blocks are then joined together using encryption to create a blockchain.[14-16] As a decentralized transaction system, BT can also facilitate data management. Secure network transactions are carried out through BT,[17,18] which does not rely on a centralized authority. This ensures data integrity, security, and transparency without intrusion from any external organization. This is one of the key reasons behind the growing interest in BT,[19-21] which in turn creates research opportunities across various fields.[16,17] In addition, homomorphic encryption enables computations to be performed on encrypted data without the need for decryption, enabling secure processing of encrypted health-care data[22,23] while preserving privacy and facilitating analysis and insights.

Below are the contributions of the proposed privacy preservation (PP) model for EHR using BT:

(i) A new PP model is proposed, which introduces an improved association rule (ASR) mining (ARM) method for mining rules. This avoids data leaks and addresses the complexity of interpreting results. In addition, it can uncover complicated and subtle associations in the data and manage data variations over time

(ii) The model introduces the Siberian Tiger Integrated Tuna Swarm algorithm (STI-TSA) optimization for optimal key generation by including the concepts of Secretary Bird Optimization (SBO) and the Tuna Swarm algorithm. The STI-TSA optimization could attain faster convergence and create high-quality solutions.

The review of PP with BT is presented in Section 2. An overview of the proposed work is provided in Section 3. Improved ARM and STI-TSA are explained in Sections 4 and 5, respectively. Data restoration is explained in Section 6. The results and conclusions are presented in Sections 7 and 8.

2. Literature review

Bio-inspired metaheuristic algorithms have recently gained significant attention as effective tools for resolving challenging optimization issues. The Tuna Swarm Optimization (TSO), introduced by Xie *et al.*,[24] improves global optimization performance by imitating the hunting and foraging habits of tuna fish. Their research showed how effective TSO is at solving a range of benchmark and practical optimization issues. The Siberian Tiger Optimization (STO) algorithm, proposed by Trojovský *et al.*,[25] was motivated by the predatory tactics of Siberian tigers. This algorithm demonstrated its ability to handle difficult optimization tasks by performing exceptionally well in engineering optimization problems. The combination of these naturally inspired methods demonstrates the continuous progress in evolutionary computing and swarm intelligence.

In 2021, Verma[26] presented a unique blockchain system to secure health records in the cloud. This technology ensured the authentication and integrity of medical information. To achieve this, they employed an enhanced Blowfish model that ensured authentication features were used to install blockchain with the best encryption. In addition, a novel method known as the Elephant Herding Optimization with Opposition-based Learning (EHO-OBL) was used to generate optimal keys. Thus, the created technique preserved the integrity of the data, and the superiority of the proposed approach was demonstrated through various performance metrics.

In 2023, Irshad *et al.*[27] proposed data restoration and sanitization procedures to generate keys from the collected data, creating an objective function for the information preservation ratio (IPR), modification degree (MD), and hiding failure rate (HFR). To ensure robust security when transferring health-care data to the cloud, they employed the bee-foraging learning particle swarm optimization (BFL-PSO) method to identify the optimal key.

Large datasets have necessitated the development of effective data mining and privacy-preserving methods. A reference point for assessing machine learning models in health-care analytics is the University of California Irvine Heart Disease dataset.[28] An enhanced ARM approach was proposed by Zhao *et al.*[29] to improve the effectiveness of pattern finding in huge datasets, showing notable gains in accuracy and processing time. To improve data security in cloud contexts, Ahamad *et al.*[30] presented a multi-objective PP model that uses a hybrid Jaya-based Shark Smell Optimization technique. Furthermore, a modified Apriori approach was introduced by Baffour *et al.*[31] to speed up and increase the accuracy of frequent itemset creation. These studies collectively contribute to the advancement of data mining, security, and optimization techniques in handling large-scale data.

A new scheme that employed medical experts to monitor patient data and provide extra units was proposed by Saraswat *et al.*[32] in 2023. Several experiments were conducted to evaluate the performance of the suggested model, and the results show that the proposed method can efficiently handle a large dataset with minimal latency. The proposed research achieved 98% maximum efficiency, 95% transaction latency, 96% overall system execution time, 92% data security, and 95% data scalability.

In 2023, Alsuqaih *et al.*[33] proposed a secure PP diagnostic technique for e-health websites that utilized BT. The suggested work offered a functional access control system, which may allow data owners to specify access controls for their private medical data. Users can efficiently add or remove authorized physicians using their user interactions for key generation. Security evaluations and experimental data demonstrate the suitability of the suggested health-chain framework for intelligent health-care systems. The comprehensive experimental analysis highlights BT's computing efficiency and resilience against various security breaches.

In 2024, Wang[34] skillfully modified data structures to meet the changing requirements of storage control and safe access. He used a unique data structure called the Enhanced Merkle Tree (EMT). To meet the needs of e-healthcare systems (e-HS), Wang adapted the traditional MT design employed by BT. The EMT significantly enhanced data integrity control and strengthened data security for access and storage. With several branches, leaves, and an individual root node, the consistent three-degree MT enables updated data validation, verification, and authentication processes. When the suggested approach was used in the e-HS, the suggested EMT performed better than existing techniques, obtaining a minimum validation duration of 14.26 m for 100 exchanges. As a result, this research advanced the discussion on privacy by offering a creative and practical solution specifically designed to address the unique challenges faced by e-HS.

A blockchain-inspired, safe, and dependable data exchange architecture for the cyber-physical medical industry 4.0 was introduced by Kumar *et al.*[35] in 2023. To enhance Healthcare 4.0, the suggested system used various encryption methods. In addition, a secure health-care architecture powered by blockchain was proposed to manage and access patient and physician information. A patient-centric approach was used to create a blockchain-oriented EHR exchange system. This implied that the owner retains complete ownership over their data, with BT providing security and privacy. According to testing findings, the suggested design can withstand various security threats and restore data, even if two or three nodes fail. The suggested paradigm was patient-centric, ensuring that even system administrators cannot access data without user authorization. This approach empowers patients with control over their data, improving security and privacy.

For increased security and scalability, Sutradhar *et al.*[36] proposed an access and identity management framework. Large data volumes and numerous applications may be supported by the suggested method, which made it a scalable and safe way to control accessibility to the Fabric system. Furthermore, to protect patient privacy and confidentiality, this system used role-based access restrictions depending on the patient's function. The statistical research showed that the suggested method can effectively and safely handle patient information and access, which might revolutionize the health-care sector by boosting data interoperability and strengthening patient security and privacy.

A secure and confidential Global Network Record-sharing consortium blockchain-sequential minimal optimization technique for diagnostic enhancements in Cyber-Physical System e-HS that utilizes the BT was presented by Hemalatha *et al.*[37] in 2023. They used two different strategies, such as consortium blockchains, which were constructed through the creation of consensus procedures and data structures. The public key was secured with keyword search to safeguard data, maintain privacy, manage access, and provide a secured search. The security analysis indicated that the proposed protocol can meet the security objectives. Furthermore, Apache JMeter was used to evaluate the efficacy of the proposed technique. The suggested effort has a 99% forecast accuracy rate at a fair time cost.

In 2023, Yi[38] introduced a cloud-based system, including post-quantum searchable encryption, in which key generation utilizing Physical Unable Functions was a part of it. Medical records were encrypted and stored in the cloud, whereas records were verified by BT and retrieved through the cloud. A safe and effective cloud-oriented health data system was suggested for digital twins by combining cloud encryption, blockchain verification, and cloud retrieval. Compared to similar concepts, this implementation shows that the system offered consumers safe and effective medical record services. This demonstrated how digital twins may revolutionize health care by enabling safe, data-driven, individualized planning, diagnosis, and treatment.

A blockchain-orchestrated deep learning (DL) technique for secure data transmission in an Internet of Things-enabled health-care system was created in 2023 by Kumar *et al.*[39] This approach was referred to as "BDSDT." In particular, by utilizing the Zero Knowledge Proof technique, a unique adaptable BT was suggested to guarantee confidentiality as well as safe data transfer. To identify intrusions in the HS network, a DL method was designed using the verified data. Then, an efficient intrusion detection system was created by combining bidirectional long short-term memory with deep sparse autoencoder.

The rapid adoption of ubiquitous computing and mobile communication has led to the emergence of mobile health, while urbanization has driven the development of smart cities. The concept of smart health integrates these two trends, creating a context-aware health-care system within smart cities to enhance service efficiency and human-centered care.[40] Context-aware health-care systems that utilize context awareness in smart health-care applications emphasize the importance of user demographics, location, and medical history, which aligns with the concept of smart health within smart cities.[41] With the rapid development of machine learning for the detection of diseases using imaging scans,[42,43] patient records have become an invaluable resource. It facilitates diagnostics, leading to the development of artificial intelligence-based medical techniques. EHRs are simpler to access and manage than paper records, but more caution is needed to ensure that the privacy of the data is maintained. Because of their centralized architecture, traditional and modern EHR systems, which are utilized for exchanging data between medical participants (patients, doctors, insurers, pharmaceuticals, doctors, and researchers), have security and privacy flaws. To prevent breaches of information privacy, several clinics and institutions have prohibited medical data transfer and exchange. Data barriers have arisen as a consequence of health data being dispersed among several health-care providers, exacerbated by concerns over health-care data security and privacy. As a result, BT is proposed as a solution, using encryption to guarantee the security and privacy of EHR systems. BT overcomes the limitations of traditional centralized systems, which are often inaccessible. The existing health-care system is perceived as complicated and expensive, but BT can mitigate these issues by enhancing insurance management and data handling. Furthermore, the decentralized nature of this system eliminates central attack points and reduces the risk of system failures.

3. PP of EHRs using BT

EHRs are digital patient records stored on networks. Still, current storage methods have proven to be quite vulnerable, where hackers and other unapproved parties can readily access the data. This vulnerability not only compromises patient data but restricts access for patients and health-care professionals. The existing approaches are unable to strike a compromise between data accessibility and security. However, BT offers a promising solution to these problems. Blockchain establishes an immutable ledger system that enables decentralized transaction processing. A novel PP technique is proposed for securing EHR, with stages shown in Figure 1.

Initially, the improved ARM approach is used to analyze medical data and find the ASRs between the data characteristics. These rules are important since they aid in identifying sensitive items in the dataset. Improvement in ARM approaches improves the process and guarantees a more precise identification of patterns in sensitive data. After identifying the ASRs, the SBI-TSA method is developed to identify the optimal keys, which are employed to encrypt and decode sensitive data. These optimal keys are derived by considering IPR, HFR, and MD.

The sensitive data are subjected to an exclusive OR (XOR) operation for sanitization using the optimal keys. This sanitized data is then stored on a blockchain. This phase ensures that the stored data cannot be decrypted without the matching key, even in the event of illegal access. When retrieval is necessary, the sanitized data undergoes a reverse XOR process with the optimal key, restoring it to its original format. This decryption process allows authorized individuals to safely access and use the information.

4. Data sanitization using improved ARM

Assume the medical dataset as d^s and D_t as the data within the dataset. This medical data D_t ($D_i = \{D_1, D_2, \ldots D_n\}$) is initially processed using the improved ARM. Data sanitization is vital for conserving privacy by sanitizing data D_t. Sanitization includes precisely identifying the sensitive information within the data to protect data privacy while preserving the data validity.

4.1. Conventional ARM

ARM analyzes input medical data D_t to find significant correlations or links between different elements, including diseases, therapies, indications, and other factors. By finding important patterns in huge datasets, this approach seeks to provide insights that might improve patient care and decision-making. These methods selectively hide some ASRs that may otherwise

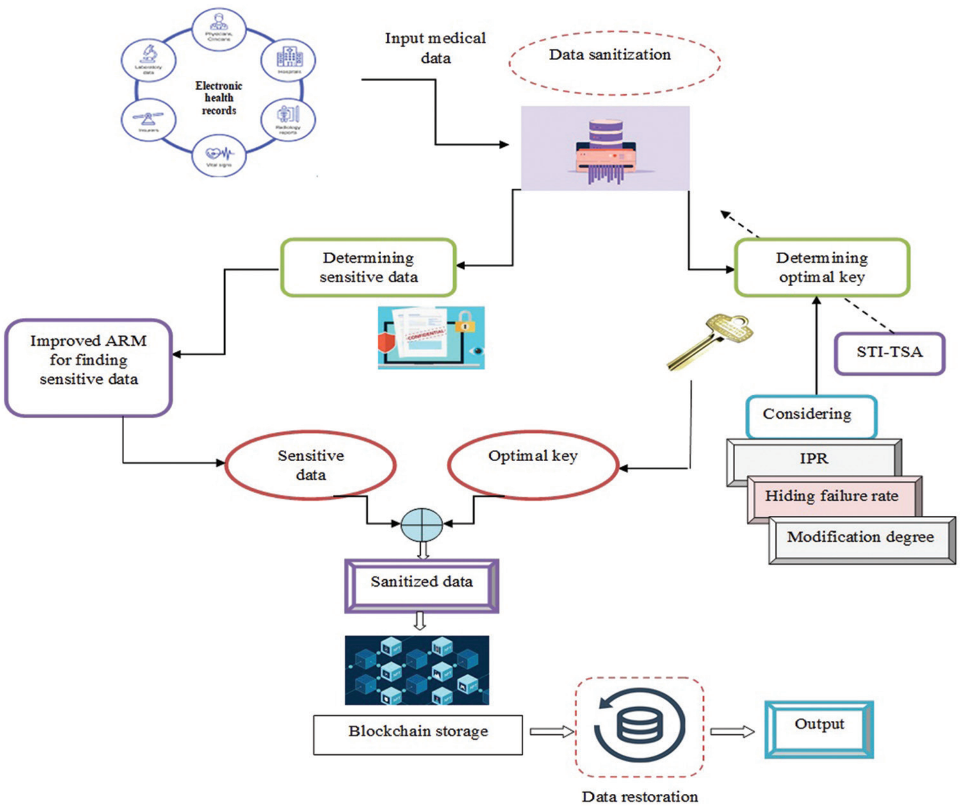

Figure 1. The architecture of privacy preservation for electronic health records using blockchain technology
Abbreviations: ARM: Association rule mining; IPR: Information preservation ratio; STI-TSA: Siberian tiger integrated tuna swarm algorithm.

uncover delicate patterns seen in the medical data D_i. The section that follows provides a thorough procedural description, and Figure 2 displays the flow chart for conventional ARM.[37]

(i) Step 1: Frequent item set generation
The first step is to identify frequent distinct items. Items that meet a minimum support threshold (MST), "minsup," are noted as M (1). Recognize the frequent items (M [1]) that occur in transactions with a threshold equal to or greater than the "minsup" threshold.

(ii) Step 2: Candidate item (CI) generation
The frequent item sets identified in Step 1, (M [1]), should be used to generate CI (F^i [L + 1]). Merge frequent item sets of length l (from M [L]) to generate CI with length $L + 1$. Eliminate any CI that contains subsets that are not frequent, those that do not exist in M (L).

(iii) Step 3: Examining support in the database
The transaction database D^{base} is scanned to count the occurrence of individual CI (F^i [L + 1]). Compute the support of every CI (F^i [L + 1]) by evaluating the transactions. If CI support is above or equivalent to "minsup," it is said to be a frequent item set and summed to M [L + 1].

(iv) Step 4: Iteration and completion
Repeat Steps 2 and 3 until no further frequent item sets M [L + 1] can be created. The anticipated result is the combination of entire frequent item sets attained across diverse lengths: the union of M [1] and M [2]. The process stops when no novel frequent item sets (M [L + 1]) are generated.

The ultimate result is derived by merging every frequent item set revealed during the iterations. The frequent item sets jointly signify the associations in d^s that satisfy the MST.

However, the traditional ARM method is more susceptible to data leaks and suffers from interpretation complexity. This might result in poor-quality data that causes erroneous rules, leading to imprecise transaction records.

To overcome these drawbacks, an improved ARM method is introduced in this work. The improved ARM could mine the rules quicker with large datasets. It

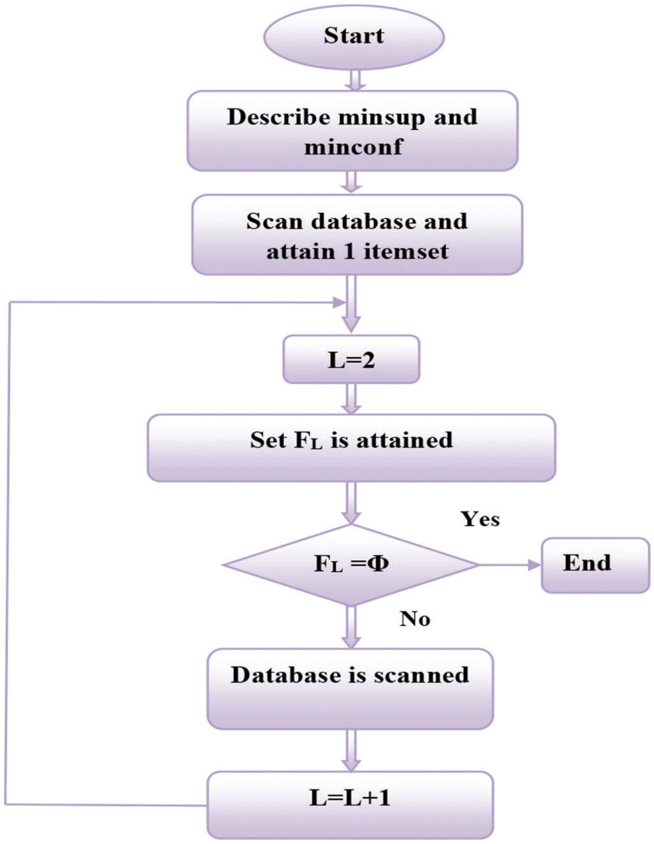

Figure 2. Flowchart for conventional association rule mining

Abbreviations: L: Length; minsup: Minimum support threshold.

creates more meaningful and precise rules. The improved ARM could identify complicated and subtle associations in the data and manage data variations over time. The procedure for the improved ARM is detailed below.

4.2. Improved ARM

The proposed improved ARM is detailed below with a flowchart representation illustrated in Figure 3.

(i) Initialization and database scanning

Initiate the process by scanning the dataset to detect frequent items that fulfill a predetermined MST. The MST is assessed in Equation I, where *Maxi* and *Mini* refer to maximum and minimum threshold values. Table 1 shows an exemplary demonstration of MST computation.

$$MST = (Maxi + Mini)/2 \quad \text{(I)}$$

In Table 1, the maximal occurrence is seven, and the minimal occurrence is two. The mean of these values is computed in Equation II.

$$MST = \frac{(7+2)}{2} = 4.5 \simeq 5 \quad \text{(II)}$$

In Table 2, the frequent items are identified as Items A and B, with a value of seven each, surpassing the MST of 5. Likewise, Item C has a value of 6 that surpasses the MST. Subsequently, an array is formed to store these frequent items. Based on Table 2, the uncommon items are eliminated. Subsequently, Table 3 shows a sample dataset, and Table 4 reveals the sample dataset after eliminating the uncommon items.[39]

(ii) Generating combinations.

After eliminating the uncommon items, the frequent items are united, as shown in Table 5.

After implementing the procedure of combination generation, the following stage is dynamic itemset counting.

(iii) Dynamic itemset counting:

The blank item sets are spotted with a solid box. All the item sets are spotted in dashed rounds. The transaction experimental values that range from 1 to 55 are read and marked with a dashed circle. When the count of dash circles goes beyond the threshold, it turns into a dash square. The support threshold (*ST*) is computed as in Equation III, where *TSC* denotes the total count of transactions.

$$ST = \left\{ \left[\frac{MST}{100} \right] \times TSC \right\} \quad \text{(III)}$$

Item sets that appear frequently in the transactions are regarded as frequent, and after the final count, these sets are identified as solid. After dynamic item set counting, the item set is represented as a Boolean matrix, which is then converted to its 2's complement. The subsequent stage checks for redundant items in the dataset. If yes, eliminate redundant items using transaction compression methods. If not, continue to the following step of database scanning.

Fix L size as 2 and item set F_j is attained. If $F_j = 0$, remove redundant item sets using transaction compression approaches. Otherwise, continue to the following step of database scanning and increase L by 1.

Replicate the procedure of producing and verifying CI F_j till no further item sets that meet the MST can be identified. The algorithm halts when no novel F_j can be created. Thus, the ASR is created through improved ARM. After creating *ASR*, the next step involves extracting the sensitive data P^d. Thus, from *ASR*, the sensitive data P^d is obtained.

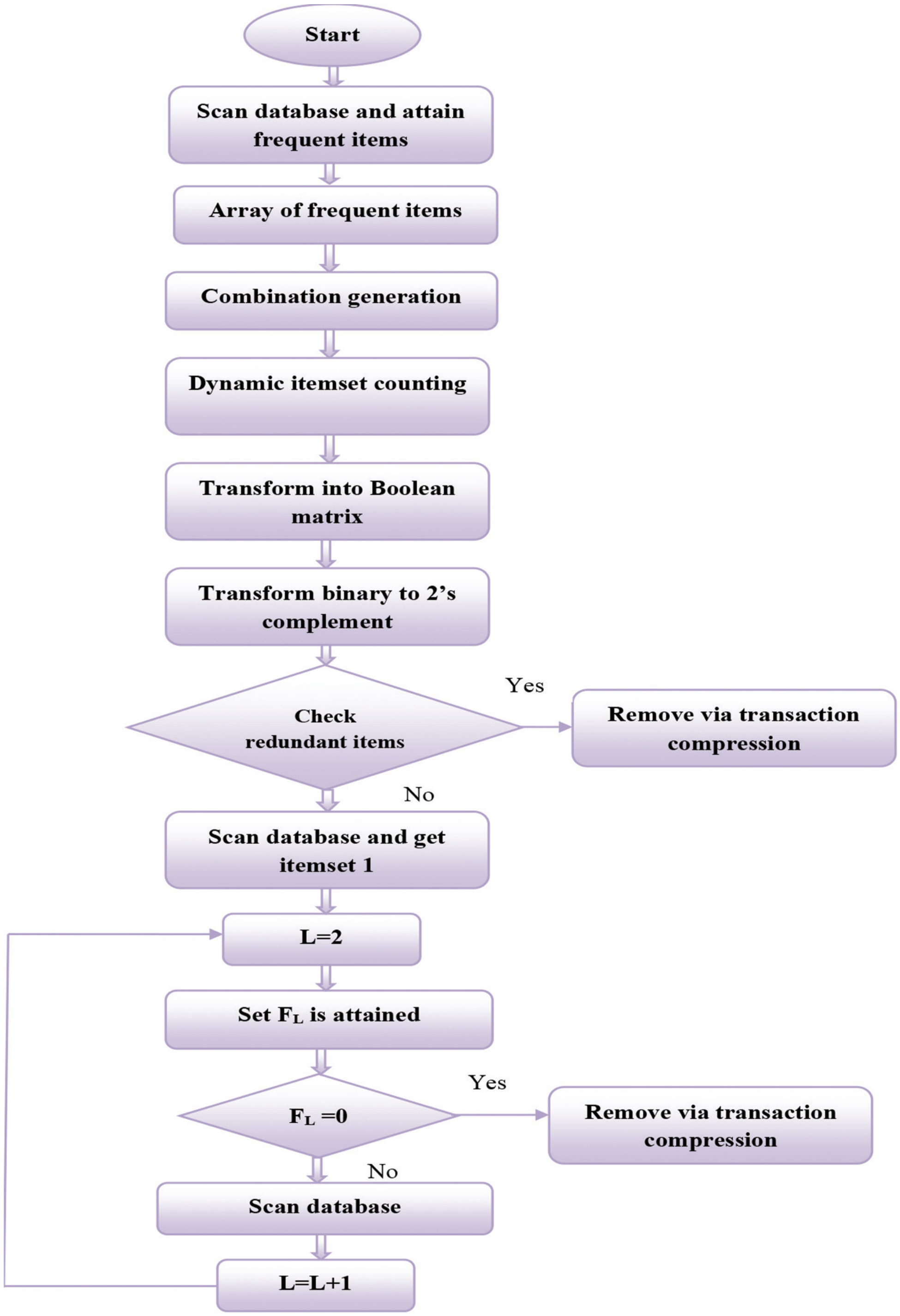

Figure 3. Flowchart for proposed improved association rule mining
Abbreviation: L: Length.

5. STI-TSA for optimal key generation

Following the extraction of sensitive data P^d, optimum keys are produced based on certain constraints. The goal of optimal key generation is to generate or choose keys that optimize utility while lowering the possibility of privacy violations. The STI-TSA technique is deployed for optimal key generation, taking into account HFR, MD, and IPR. The STI-TSA method aids in the identification of keys, ensuring that the optimal keys are strong and well-designed to satisfy both operational and security criteria.

Table 1. Example of minimum support threshold computations with items and their occurrences

Item	Occurrence
A	7
B	7
C	6
D	2
E	4
F	4

Table 2. Frequent items and occurrences

Items	Occurrence
A	7
B	7
C	6

Table 3. Sample dataset

Item 1	Item 2	Item 3	Item 4	Item 5
A	B	C		
A	C			
B	D	E		
A	C	F		
A	B	C	D	E
B	F			

Table 4. Dataset after eliminating the uncommon items

Item 1	Item 2	Item 3	Item 4	Item 5
A	B	C		
A	C			
B				
A	C			
A	B	C		
B				

Table 5. Generation of item combinations

Row 1: AB, AC, BC
Row 2: AC
Row 3: -
Row 4: AC
Row 5: AB, AC, BC
Row 6: -

5.1. Objective function

The STI-TSA is deployed to generate optimal keys for PP. This algorithm takes into account HFR, MD, and IPR. Consequently, the objective function is represented by Equation IV, where weight is denoted by *w*.

$$OF = \min\left(W_1 \times [1 - IPR] + W_2 \times HFR + W_3 \times MD\right) \quad \text{(IV)}$$

In Equation IV,

$$W_i = \frac{Constraints_i}{Sum\ of\ constraints_{(i)}} \quad \text{(V)}$$

HFR is the proportion of sensitive data P^d to the total count of P^d in d^s, as well-defined in Equation VI. In Equation VI, P^* specifies the sanitized data.

$$HFR = \frac{Count\ of\ sensitive\ data\ exposed\ in\ P^*}{Count\ of\ sensitive\ data} \quad \text{(VI)}$$

MD[38] offers specifics on the degree of modification happening among P^d and P^*, as shown in Equation VII.

$$MD = \text{Euclidean}\ [P^D, P^*] \quad \text{(VII)}$$

The IPR indicates the variance between the count of non-sensitive data and P^* to the total count of non-sensitive data in Equation VIII.

$$IPR = \frac{Non-sensitive\,data\,count - P^*}{Non-sensitive\,data\,count} \quad \text{(VIII)}$$

5.2. Solution encoding

During optimization, candidate keys are provided as input to the STI-TSA. During optimization, STI-TSA refines the keys continuously based on certain constraints that prioritize effective PP. The iterative procedure of STI-TSA strikes a balance, ensuring the candidate keys meet the objectives of preserving privacy in EHRs.

5.2.1. STI-TSA

Tuna search for their prey using two different foraging techniques. Initially, the population in the field of search space is generated arbitrarily for the TSA's optimization. Each tuna chooses one of the two foraging techniques to use. All TSA individuals were kept informed until the final requirement was fulfilled. The optimal solution and the corresponding fitness value were then returned. This section describes the precise model of the STI-TSA.

While the TSA offers better solutions, it is prone to converging to local optima instead of finding the global optimum. Moreover, excessive exploration can cause the algorithm to miss the optimal solution, whereas too much exploitation may result in getting stuck in local minima. Therefore, to overcome these challenges, we included the concept of STO in our work.

The new algorithm, including the concepts of SBO[33] and TSA,[32] is termed STI-TSA. The hybrid TSA with SBO could attain faster convergence and create high-quality solutions, including diverse optimizing approaches. In addition, STI-TSA could balance both local and global searches.

(i) Initialization: TSA begins with the arbitrary generation of initial populations as shown in Equation IX, where, Z_l^{in} points out initial individuals, *LB* and *UB* point out lower and upper limits, *O* points out the tuna population, and *rnd* points out random values between 0 and 1

$$Z_l^{\text{in}} = rnd.\left(UB - LB\right) + LB,\ \ l = 1,2...O \tag{IX}$$

(ii) Spiral foraging: The entire school of fish forms a tight configuration by continuously changing its swimming direction to prevent predators from latching onto a victim. At that point, the tuna group forms a tight spiral shape to pursue the prey. Although many fish possess a sense of direction, when a small group of fish begins swimming in a certain direction, other fish in the vicinity often follow suit. The fish in the leading group share a common objective and initiate the hunt. Furthermore, all tuna communicate with each other. The mathematical formula for spiral foraging behavior is provided in Equation X.

$$Z_l^{T+1} = \begin{cases} \gamma_1 \cdot \left(Z_{best}^T + \delta.\left|Z_{best}^T - Z_l^T\right|\right) + \gamma_2.Z_l^T, & l = 1 \\ \gamma_1 \cdot \left(Z_{best}^T + \delta.\left|Z_{best}^T - Z_l^T\right|\right) + \gamma_2.Z_{l-1}^T & l = 2,3,...,O \end{cases} \tag{X}$$

The computation of γ_1, γ_2, δ, and *le* are shown in Equation XI to Equation XIV.

$$\gamma_1 = co + \left(1 - co\right).\frac{T}{T_{\max}} \tag{XI}$$

$$\gamma_2 = \left(1 - co\right) - \left(1 - co\right).\frac{T}{T_{\max}} \tag{XII}$$

$$\delta = w^{ble}.\cos\,(2\pi b) \tag{XIII}$$

$$le = w^{3\cos\left(\left(\left(T_{\max} + 1/T\right) - 1\right)\pi\right)} \tag{XIV}$$

Here, l^{th} individual at $T + 1$ iteration is signified by Z_l^{T+1}, whereas Z_{best}^T symbolizes the current optimal individual, and γ_1 and γ_2 symbolize weighting coefficients. The extent to which tuna follows the optimal and prior individual is assessed by *co*, whereas T and $T_{\max}$ signify the iteration count and maximal iteration, and *b* signifies the random figure between 0 and 1.

Each tuna can more effectively utilize the search phase when swimming in a spiral pattern around the bait. This strategy allows the tuna to cover a larger area, enhancing TSA's potential to explore the search space on a global scale, as stated in Equation XV.

$$Z_l^{T+1} = \begin{cases} \gamma_1 \cdot \left(Z_{rnd}^T + \delta.\left|Z_{rnd}^T - Z_l^T\right|\right) + \gamma_2.Z_l^T, & l = 1 \\ \gamma_1 \cdot \left(Z_{rnd}^T + \delta.\left|Z_{rnd}^T - Z_l^T\right|\right) + \gamma_2.Z_{l-1}^T & l = 2,3,...,O \end{cases} \tag{XV}$$

The symbol Z_{rnd}^T represents an arbitrary reference point in the field of search space. The TSA changes the spiral foraging indicators from arbitrary to optimum ones as the iteration rises. It may be found numerically in Equation XVI.

$$Z_l^{T+1} = \begin{cases} \gamma_1 \cdot \left(Z_{rnd}^T + \delta.\left|Z_{rnd}^T - Z_l^T\right|\right) + \\ \gamma_2.Z_l^T,\ l = 1, \\ \gamma_1 \cdot \left(Z_{rnd}^T + \delta.\left|Z_{rnd}^T - Z_l^T\right|\right) + & ,if\ rnd < \dfrac{T}{T_{\max}}, \\ \gamma_2.Z_{l-1}^T,\ l = 2,3,...,O, \\ \gamma_1 \cdot \left(Z_{best}^T + \delta.\left|Z_{best}^T - Z_l^T\right|\right) + \\ \gamma_2.Z_l^T,\ l = 1 \\ \gamma_1 \cdot \left(Z_{best}^T + \delta.\left|Z_{best}^T - Z_l^T\right|\right) + & ,if\ rnd \geq \dfrac{T}{T_{\max}}, \\ \gamma_2.Z_{l-1}^T,\ l = 2,3,...,O \end{cases} \tag{XVI}$$

(iii) Proposed parabolic foraging: Here, tuna forms a parabolic shape using food as a point of reference. They also search their surroundings in search of nourishment. Two methods were used simultaneously, with the assumption that each had a 50% chance of being selected. Its numerical version is given in Equation XVII. *tf* is an arbitrary number with a value of either −1 or 1.

$$Z_l^{T+1} = \begin{cases} Z_{best}^T + rnd.\left(Z_{best}^T - Z_l^T\right) + \\ tf.\left(A\right)^2.\left(Z_{best}^T - Z_l^T\right), & if\ rnd < 0.5, \\ tf.\left(A\right)^2.Z_l^T, & if\ rnd \geq 0.5, \end{cases} \quad \text{(XVII)}$$

$$A = \left(1 - \frac{T}{T_{\max}}\right)^{\left(T/T_{\max}\right)} \quad \text{(XVIII)}$$

As per STI-TSA, Equation XVIII is converted, as shown in Equation XIX.

$$\begin{array}{l} Z_l^{T+1} = Z_{best}^T + rnd.\left(Z_{best}^T - Z_l^T\right) + tf.\left(A\right)^2.\left(Z_{best}^T - Z_l^T\right) \\ +Z_l^{T+1} = tf.\left(A\right)^2.Z_l^T \\ \hline 2Z_l^{T+1} = Z_{best}^T + rnd.Z_{best}^T - rnd.Z_l^T + tf.\left(A\right)^2.Z_{best}^T \end{array} \quad \text{(XIX)}$$

Finally,

$$Z_l^{T+1} = \frac{Z_{best}^T + rnd.Z_{best}^T - rnd.Z_l^T + tf.\left(A\right)^2.Z_{best}^T}{2} \quad \text{(XX)}$$

Furthermore, the update from the modified STO is integrated with TSA to form a new update. The update from the modified STO is shown in Equation XXIII.

$$Z_{i,j}^{p1s2} = Z_{i,j} + R_{i,j}.\frac{\left(UB_j - LB\right)}{T},\ i = 1,2...N,\ j = 1,2...B \quad \text{(XXI)}$$

$$Z_{i,j}^{p1s2} = Z_{i,j} + \frac{R_{i,j}.UB_j}{T} - \frac{R_{i,j}.LB_j}{T} \quad \text{(XXII)}$$

$$Z_{i,j} = Z_{i,j}^{p1s2} - \frac{R_{i,j}.UB_j}{T} + \frac{R_{i,j}.LB_j}{T} \quad \text{(XXIII)}$$

On substituting Equation XXIII in Equation XX, we get Equation XXVIII.

$$Z_l^{T+1} = \frac{Z_{best}^T + rnd.Z_{best}^T - rnd.\left[Z_{i,j}^{p1s2} - \frac{R_{i,j}.UB_j}{T} + \frac{R_{i,j}.LB_j}{T}\right] + tf.\left(A\right)^2.Z_{best}^T}{2} \quad \text{(XXIV)}$$

$$Z_l^{T+1} - \frac{rnd\, Z_{i,j}^{p1s2}}{2} = \frac{Z_{best}^T + rnd.Z_{best}^T + rnd.\frac{R_{i,j}.UB_j}{T} - rnd.\frac{R_{i,j}.LB}{T} + tf.\left(A\right)^2.Z_{best}^T}{2} \quad \text{(XXV)}$$

$$Z_l^{T+1}\left[1 + \frac{rnd}{2}\right] = \frac{Z_{best}^T + rnd.Z_{best}^T + rnd.\frac{R_{i,j}.UB_j}{T} - rnd.\frac{R_{i,j}.LB_j}{T} + TF.\left(sf\right)^2.Z_{best}^T}{2} \quad \text{(XXVI)}$$

$$Z_l^{T+1}\left[1 + \frac{rnd}{2}\right] = \left[\frac{Z_{best}^T + Z_{best}^T\left(rnd + tf.\left(A\right)^2\right) + rnd.\frac{R_{i,j}.UB_j}{T} - rnd.\frac{R_{i,j}.LB_j}{T}}{2}\right] \quad \text{(XXVII)}$$

Finally,

$$Z_l^{T+1} = \frac{\left[\frac{Z_{best}^T + Z_{best}^T\left(rnd + tf.\left(A\right)^2\right) + rnd.\frac{R_{i,j}.UB_j}{T} - rnd.\frac{R_{i,j}.LB_j}{T}}{2}\right]}{\left[1 + \frac{rnd}{2}\right]} \quad \text{(XXVIII)}$$

Here, Equation XXVIII replaces Equation XVI.

On hybridizing TSA with SBO, faster convergence could be attained and high-quality solutions could be created by including diverse optimizing approaches. In addition, STI-TSA could balance both local and global searches.

The pseudocode for STI-TSA optimization is shown in Algorithm 1.

Algorithm 1: Siberian Tiger Integrated Tuna Swarm algorithm

Initializing the population
Initializing$_{co}$ and probability I
While T <$Tmax$
  Compute fitness
  Update Z_{best}^{T}
  For every tuna
    $\gamma 1$, $\gamma 2$, and A are updated
    If rnd <I
    Position is updated through Equation IX
    Else if rnd ≥I
      If rnd <0.5
        If $\frac{T}{T_{\max}} < rnd$
          Position is updated through Equation XV
        else
          Position is updated through Equation X
      Else if rnd ≥0.5
        Position is updated through proposed Equation XXVIII by integrating the update of STO
  End for
T=T + 1
Return the best solution

From STI-TSA, the optimal key K^o is attained.

(iv) Sanitization process: The XOR operation among sensitive data P^d and the optimum key K^o yields the sanitized data as given in Equation XXIX. By successfully masking the original data, this bitwise operation improves security and privacy. From Equation XXIX, P^* implies the output sanitized data.

$$Sanitized\ data\left(P^*\right) = P^d \oplus K^o \quad \text{(XXIX)}$$

6. Blockchain-based sensitive data storage

(i) Block creation: Sanitized data are grouped into blocks. Each block may contain multiple encrypted records
(ii) Hashing: Each block is hashed to generate a unique digital fingerprint. The hash includes the block's data and the hash of the previous block, creating a chain of blocks
(iii) Block addition: The block is added to the blockchain after being verified by the network's consensus mechanism
(iv) Access control: The access control to access the sensitive data is given below:
  a. Public and private keys: Patients have private keys K^o (optimal key) that allow them to decrypt their health records. Health-care providers have their keys to access the data as well
  b. Permission management: Access to the data is controlled through a system of permissions. For instance, a patient's consent is required before a health-care provider can access or update their records. The process of restoring the original data is discussed below.

7. Data restoration

Reversing the steps taken throughout the privacy-preserving stage is the last step in the process of recovering the original data. Recovering sensitive data while protecting data privacy requires this procedure. The formula for obtaining the original data using the reverse procedure is given in Equation XXX.

$$P^d = P^* \oplus K^o \quad \text{(XXX)}$$

Using an optimal key generated from ASRs, the XOR operation is crucial in concealing sensitive data during data sanitization. The inverse XOR procedure needs to be used to recover the original sensitive data. Employing the inverse XOR, the sanitized data are broken down in this reverse process, guaranteeing an exact reconstruction of the original data. Similar to this, ASRs that recognize delicate patterns in the data are produced using the improved ARM algorithm. Reverse algorithms or processes capable of reversing the impact of these privacy-preserving approaches are used to return the original data from its sanitized version. This preserves the sensitive data while guaranteeing that initial medical data D_i may completely be retrieved for additional examination or use.

8. Results and discussion

8.1. Simulation procedure

The introduced approach for PP for EHR using BT was executed in Python. The simulation was run on a system equipped with an 11th Gen Intel(R) Core (TM) i3-1115G4 @ 3.00 GHz processor and 8.00 GB (7.74 GB usable) of RAM. The assessment was conducted using STI-TSA, comparing its performance against STO, TSA, Puffer Fish Optimization (PFO), SBO Algorithm (SBOA), Bat Algorithm (BA), EHO-OBL,[34] and BFL-PSO.[35] The dataset used in this study is the Heart Disease dataset from the UCI Machine Learning Repository.[36]

This database contains 76 attributes, but previous experiments have focused on a subset of 14. The goal field refers to the presence of heart disease in the patient, with integer values ranging from 0 (no presence) to 4. The names and social security numbers of the patients were recently removed from the database and replaced with dummy values. One processed file containing the Cleveland database is available, while the remaining four unprocessed files are also included in this directory.

8.2. Analysis of IPR, HFR, and MD

Figure 4 shows the performance of IPR, HFR, and MD for proposed STI-TSA optimization over extant optimization schemes, such as STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35] Regarding fitness, the IPR and HFR have to be higher for better performance, whereas MD has to be lower. From the graphs in Figure 4, it can be observed that the proposed STI-TSA-based optimization has fulfilled this statement. Particularly, the IPR is higher when data are at 30%. For datasets with 10% and 20%, the proposed STI-TSA-based optimization achieves a higher IPR compared to STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35] When data are 10%, the proposed STI-TSA-based optimization attained a high IPR of 0.93%; with 20% data, the IPR reaches 0.94%; and with 30% data, the IPR attains 0.95%. In contrast, at 30% of data, extant optimization schemes, such as STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO[35] achieved lower IPR values of 0.89, 0.9, 0.87, 0.9, 0.87, 0.89, and 0.88, respectively.

The new STI-TSA algorithm, incorporating the concepts of SBO and TSA, could attain faster convergence and create high-quality solutions that

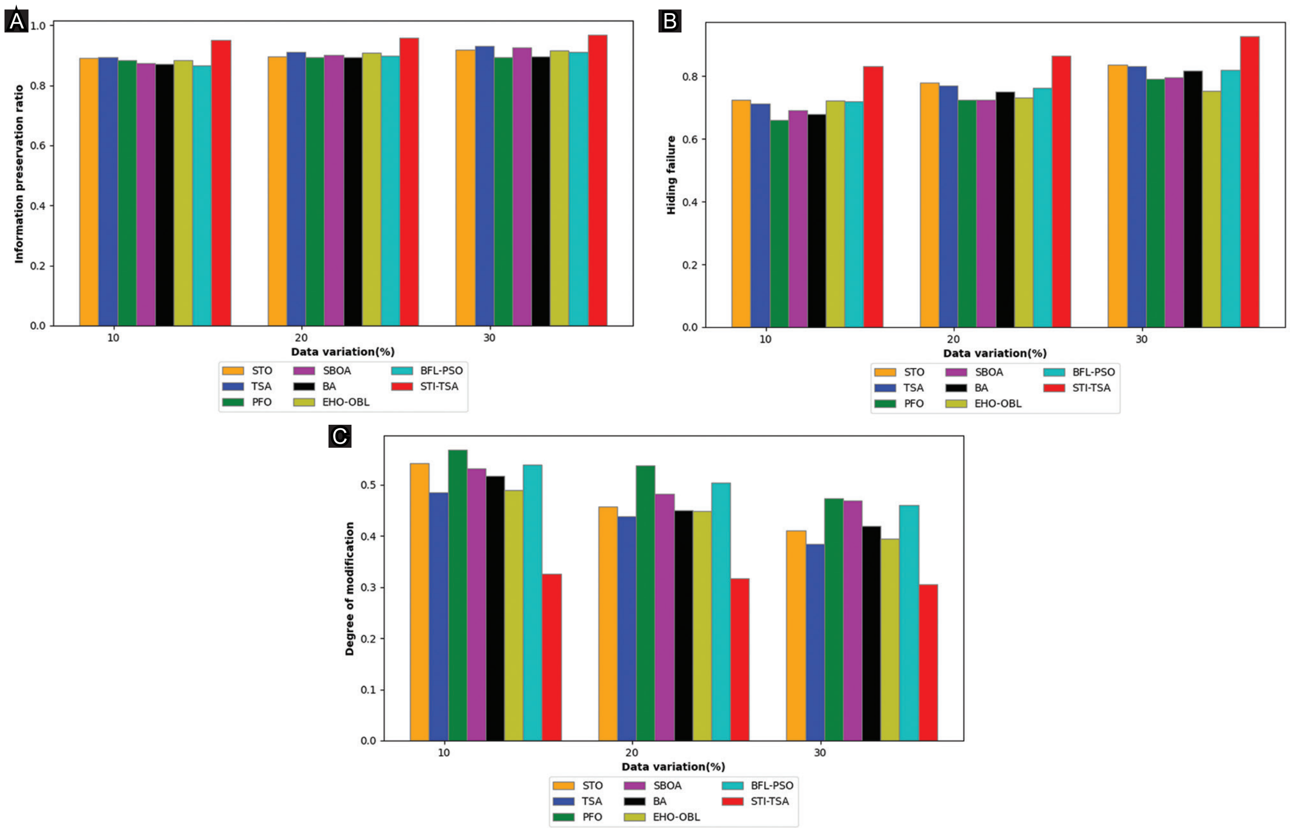

Figure 4. Performance of privacy preservation for electronic medical records using blockchain technology. Performance of the Siberian Tiger Integrated Tuna Swarm algorithm (STI-TSA) over extant optimization approached for (A) information preservation ratio, (B) hiding failure rate, and (C) modification degree.
Abbreviations: BA: Bat Algorithm; BFL-PSO: Bee-foraging learning particle swarm optimization; EHO-OBL: Elephant Herding Optimization with Opposition-based Learning; PFO: Puffer Fish Optimization; SBOA: Secretary Bird Optimization Algorithm; STO: Siberian Tiger Optimization; TSA: Tuna Swarm algorithm.

include diverse optimizing approaches. Similarly, in the case of HFR, the proposed STI-TSA-based optimization obtained a high value of 0.95 when the data were 30%. In contrast, lower HFR values were achieved when data were at 10% and 20%. However, for all data variations, the proposed STI-TSA-based optimization attained high HFR over STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35]

As required, the MD is low for the proposed STI-TSA-based optimization over STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35] A significantly low MD value (approximately 0.3) was obtained when data were at 30%, whereas extant optimization approaches obtained high MD values. Thus, with its balanced approach, STI-TSA delivers superior performance.

8.3. Ablation study

Table 6 presents the ablation study for validating the enhancement of the proposed STI-TSA with improved ARM, compared to both the version without ARM and the version with traditional ARM. After modifying the existing ARM, we achieved better performance using the improved ARM. In Table 6, the proposed STI-TSA with improved ARM shows a high IPR of 0.958626, whereas the versions without ARM and with traditional ARM show lower IPR. The improved ARM could mine the rules quicker with large datasets and create more meaningful and precise rules. The improved ARM could identify complicated and subtle associations in the data and manage data variations over time. This is evident from the HFR, where the proposed STI-TSA with the improved ARM reaches a value of 0.8645, compared to 0.792064 and 0.813284 for the versions without ARM and with traditional ARM, respectively. The MD metric using the proposed STI-TSA with improved ARM is lower (around 0.317), whereas the versions without ARM and with traditional ARM exhibit higher MD values.

8.4. Attack analysis

Table 7 presents an analysis of various attack types, namely, chosen ciphertext attack (CCA), chosen-plaintext attack (CPA), known ciphertext attack (KCA), and known-plaintext attack (KPA) with respect to key breaking time. CCA is an attack model for cryptanalysis where the cryptanalyst can gather information by obtaining the decryptions of chosen ciphertexts. CPA is an attack model for cryptanalysis that presumes that the attacker can obtain the cipher texts for arbitrary plaintexts. The goal of the attack is to gain information that reduces the security of the encryption scheme. KPA is an attack model for cryptanalysis where the attacker has access to both the plaintext (called a crib) and its encrypted version (cipher text). KCA is an attack model for cryptanalysis where the attacker is assumed to have access only to a set of ciphertexts.

A message tampering attack (MTA) entails the harmful alteration of information, whereas an eavesdropping attack (EDA) refers to the unauthorized real-time interception of private communication through modern hacking technologies. Attack analysis reflects the level of protection against these threats – lower values indicate that the attacker takes more time to decrypt the sanitized data. For all data variations, the proposed STI-TSA with improved ARM has attained lower values over extant STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35] This shows that the hacker needs more time to decrypt the sanitized data.

Table 7 presents the results of CCA, where the proposed STI-TSA with improved ARM attained a lower value of 0.227 at 30% data, compared to relatively higher values for STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO,[35] which are 0.294249, 0.286082, 0.292351, 0.290481, 0.292558, 0.323516, and 0.304436, respectively. Moreover, the 30% data shows lower attack values compared to data variations of 10% and 20%. For KCA, the proposed STI-TSA with improved ARM achieved a value of 0.218, while for KPA, it obtained a value of 0.171256. In regards to CPA, the proposed STI-TSA with improved ARM attains a low value of 0.21335. Moreover, for MTA and EDA, the proposed STI-TSA with improved ARM achieved

Table 6. Ablation analysis using Siberian Tiger Integrated Tuna Swarm algorithm with improved association rule mining over conventional works

Metrics	Proposed without association rule mining	Proposed with conventional association rule mining	Siberian Tiger Integrated Tuna Swarm algorithm with improved association rule mining
Information preservation ratio	0.912531	0.928175	0.958626
Hiding failure rate	0.792064	0.813284	0.86452
Modification degree	0.427843	0.410396	0.317007

Table 7. Attack analysis on privacy preservation with blockchain technology

Type of attack	Data variation (%)	STO	TSA	PFO	SBOA	BA	EHO-OBL	BFL-PSO	STI-TSA
Chosen ciphertext attack	10	0.351921	0.339407	0.34287	0.365965	0.349648	0.37791	0.367569	0.253009
	20	0.339255	0.308546	0.302815	0.312861	0.305106	0.341916	0.324134	0.240593
	30	0.294249	0.286082	0.292351	0.290481	0.292558	0.323516	0.304436	0.227043
Chosen-plaintext attack	10	0.377369	0.311311	0.382294	0.329612	0.374634	0.367101	0.405775	0.257965
	20	0.357544	0.296104	0.373377	0.306939	0.326005	0.336375	0.38882	0.231773
	30	0.334005	0.285204	0.355613	0.293705	0.295356	0.298582	0.37005	0.213351
Known ciphertext attack	10	0.345052	0.32823	0.340936	0.356009	0.347683	0.362589	0.372112	0.257533
	20	0.322449	0.311838	0.333301	0.327906	0.331565	0.329808	0.340978	0.236284
	30	0.293598	0.28121	0.329029	0.298151	0.317375	0.304013	0.32031	0.218906
Known-plaintext attack	10	0.358404	0.349322	0.362844	0.399397	0.391895	0.351093	0.333991	0.214906
	20	0.333724	0.315239	0.350371	0.382028	0.373978	0.342707	0.30128	0.192158
	30	0.262814	0.256571	0.308598	0.316097	0.321592	0.269359	0.279833	0.171256
Message tampering attack	10	0.431751	0.404186	0.437191	0.395072	0.435468	0.445301	0.430577	0.30485
	20	0.386429	0.363971	0.403125	0.362718	0.472377	0.401626	0.397691	0.283366
	30	0.316525	0.305065	0.335472	0.309952	0.332473	0.342722	0.330549	0.269973
Eavesdropping attack	10	0.424193	0.344404	0.412145	0.436951	0.43424	0.4271	0.36815	0.307106
	20	0.358123	0.329038	0.358288	0.395517	0.365027	0.34271	0.339393	0.293574
	30	0.318197	0.302423	0.332521	0.348741	0.332513	0.310608	0.311976	0.272066

Abbreviations: BA: Bat Algorithm; BFL-PSO: Bee-foraging learning particle swarm optimization; EHO-OBL: Elephant Herding Optimization with Opposition-based Learning; PFO: Puffer Fish Optimization; SBOA: Secretary Bird Optimization Algorithm; STO: Siberian Tiger Optimization; TSA: Tuna Swarm algorithm.

values of approximately 0.269973 and 0.272066, respectively.

8.5. Data sanitization and restoration analysis

Restoration signifies the reconstructing or recovery of data and systems to their original state after loss or corruption. When combined, they provide system recovery, data integrity, and privacy protection. The sanitization analysis and restoration analysis are shown in Tables 8 and 9, respectively. For better PP of EHR, the sanitization values must be lowered to confirm slight alteration of sensitive data. In contrast, the values of restoration must be high to enable accurate retrieval of original data. This statement is well accomplished by the proposed STI-TSA with improved ARM. In Table 8, STI-TSA with improved ARM reveals a minimal sanitization value of 0.2617 for data at 30%. At the same time, STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO[35] attain high sanitization values of 0.352917, 0.33179, 0.344319, 0.343102, 0.347302, 0.397624, and 0.368462, respectively. In the case of restoration, the proposed STI-TSA with improved ARM obtains a high value of 0.953422, while extant methods show lower restoration values.

Table 8. Data sanitization analysis on privacy preservation of electronic health records with blockchain technology

Methods	10%	20%	30%
STO	0.389357	0.389299	0.352917
TSA	0.423491	0.380429	0.33179
PFO	0.424748	0.400766	0.344319
SBOA	0.394453	0.372241	0.343102
BA	0.393901	0.363528	0.347302
EHO-OBL	0.428647	0.410471	0.397624
BFL-PSO	0.409735	0.39719	0.368462
STI-TSA	0.306117	0.287711	0.261784

Abbreviations: BA: Bat Algorithm; BFL-PSO: Bee-foraging learning particle swarm optimization; EHO-OBL: Elephant Herding Optimization with Opposition-based Learning; PFO: Puffer Fish Optimization; SBOA: Secretary Bird Optimization Algorithm; STO: Siberian Tiger Optimization; TSA: Tuna Swarm algorithm.

The low sanitization values confirm that the proposed STI-TSA with improved ARM incurs slight alteration of sensitive data over others. The high restoration values confirm the accurate retrieval of original data using the STI-TSA with improved ARM over extant ones.

Table 9. Data restoration analysis on privacy preservation for electronic health records with blockchain technology

Methods	10%	20%	30%
STO	0.850778	0.870158	0.892701
TSA	0.860621	0.881882	0.904179
PFO	0.834467	0.864743	0.876605
SBOA	0.822115	0.835485	0.862898
BA	0.814612	0.823373	0.847861
EHO-OBL	0.809184	0.824774	0.86858
BFL-PSO	0.826664	0.82739	0.886539
STI-TSA	0.933553	0.945149	0.953422

Abbreviations: BA: Bat Algorithm; BFL-PSO: Bee-foraging learning particle swarm optimization; EHO-OBL: Elephant Herding Optimization with Opposition-based Learning; PFO: Puffer Fish Optimization; SBOA: Secretary Bird Optimization Algorithm; STO: Siberian Tiger Optimization; TSA: Tuna Swarm algorithm.

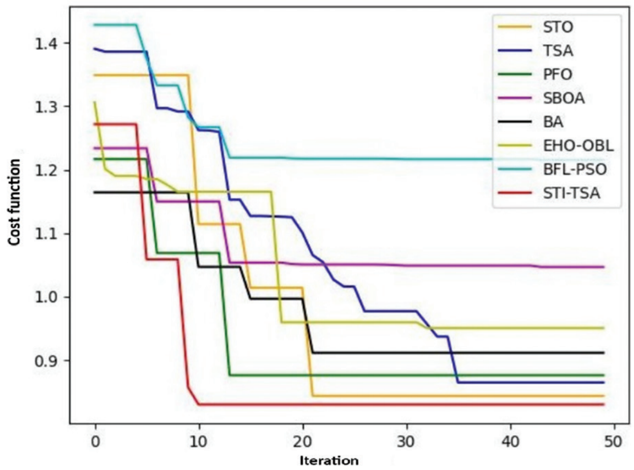

Figure 5. Convergence study of privacy preservation for electronic health records using blockchain technology. Abbreviations: BA: Bat Algorithm; BFL-PSO: Bee-foraging learning particle swarm optimization; EHO-OBL: Elephant Herding Optimization with Opposition-based Learning; PFO: Puffer Fish Optimization; SBOA: Secretary Bird Optimization Algorithm; STO: Siberian Tiger Optimization; TSA: Tuna Swarm algorithm.

8.6. Convergence analysis

Figure 5 shows the cost analysis using the proposed STI-TSA with an improved ARM over STO, TSA, PFO, SBOA, BA, EHO-OBL,[34] and BFL-PSO.[35] To ensure better PP, the cost values should be low with fast convergence. This is well accomplished using the proposed STI-TSA with an improved ARM approach. At initial iterations, the costs are high for all algorithms. However, with increasing iterations, the costs are reduced. Among all, the proposed STI-TSA with improved ARM shows lower cost values and has a faster convergence rate compared to other algorithms. Thus, the STI-TSA model could attain faster convergence and create high-quality solutions by including diverse optimizing approaches.

9. Conclusion

This work presented a novel PP approach for EHR utilizing BT. The method used an organized procedure that included data sanitization and restoration. First, improved ARM was used to detect sensitive information. The STI-TSA then finds the best key to improve data security. Sensitive information was safeguarded by applying an XOR operation among the sensitive data and the optimum key to sanitize the data. Next, blockchain storage was used to store the sanitized data. When necessary, the restoration procedure undoes the XOR operation to retrieve the original sensitive data. In the end, the reverse procedure of improved ARM was used to recover the original health data. From the analysis, when data were 10%, the proposed STI-TSA-based optimization attained a high IPR of 0.93%. In comparison, IPR of 0.94% and 0.95% were achieved when data were at 20% and 30%, respectively. At 30% of data, extant optimization schemes, such as STO, TSA, PFO, SBOA, BA, EHO-OBL, and BFL-PSO, attained low IPR of 0.89, 0.9, 0.87, 0.9, 0.87, 0.89, and 0.88, respectively. In the future, DL approaches can be integrated to improve the privacy of EHR data.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Varsha Mhaske
Investigation: Varsha Mhaske
Methodology: P. M. Ashok Kumar
Writing – original draft: Varsha Mhaske
Writing – review & editing: Varsha Mhaske

Availability of data

The data produced and analyzed in this study are available upon reasonable request from the corresponding author.

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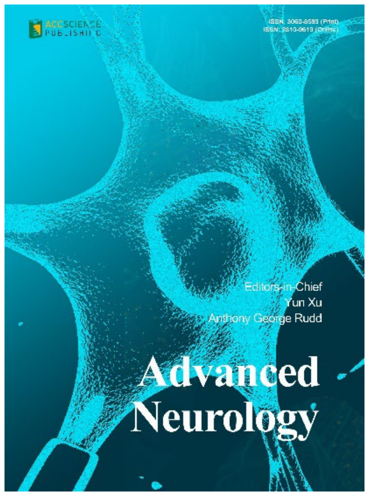
OR welcomes submissions spanning diverse areas of organoid science, including but not limited to stem cell biology, tissue engineering, regenerative medicine, disease modeling, and drug discovery. The journal encourages papers that explore bioengineered organoids, organoid-based systems biology, and the integration of organoids with clinical research. Special emphasis is placed on contributions that advance novel approaches to organoid development, including the use of cutting-edge bioengineering techniques, materiobiology, and integrative technologies such as artificial intelligence, high-throughput screening, and precision medicine. Additionally, the journal values research that delves into ethical considerations and challenges related to the clinical translation of organoid systems.

Advanced Neurology is a peer-reviewed and open-access journal that aims to publish and disseminate novel research in the breadth of neurology and neuroscience. The journal aims to advance our understanding in the nervous system and provide a platform to neuroscientists and physicians to showcase their findings in original fundamental and clinical research as well as to present new ideas that highlight the changes in the neurological clinical practice.



Advanced Neurology covers subject areas, including but not limited to the following:

- Neurological disorders
- Neurodegenerative disease
- Cerebrovascular disease
- Epilepsy and movement disorders
- Neuroimmune disease
- Neurological infections
- Muscle disease
- Molecular and cellular neuroscience
- Systems neuroscience
- Cognitive neuroscience
- Computational modeling of nervous system

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